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Prolonged Heavy Vehicle Driving Performance: Analysis of Different Types of Following Manoeuvre

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This research note examines the effects of time driving on truck drivers' behavior in a range of different following manoeuvres, and the relationship between speed and time headway in steady-state following. Three types of driving condition are included: normal, two-vehicle convoy, and unpredictable shift onset and duration.

Results of the experiments were that drivers, when adjusting (continued) headway in most types of following manoeuvres, take account of the (OVER)

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20. Abstract (continued)

probability of leading vehicle deceleration (adopting a longer headway when the possibility of such deceleration is relatively high), and of variations in on-going capability (adopting a longer headway when capability is perceived as less than optimal). Results also indicate that drivers show a preference for a headway of about 70 feet, almost irrespective of their speed.

These findings have been interpreted within the framework of a behavioral analysis of the task of driving. Implications for driver safety, selection, and training, and for driving practice are outlined. An evaluation of time headway as a measure of driver performance is presented, and some issues for future research are identified. In particular, it is suggested that much more emphasis could usefully be placed on the identification of those rewards which reinforce both safe and dangerous driving, with a view toward greater control of the driver's reward system. (SDW)

Foreword

The aim of this report is to provide a summary and overview of the results obtained in a series of re-examinations of the data of three experiments completed earlier by the author. A brief attempt will be made to provide a conceptual framework which ties together the main findings of the study; to explore the implications of the results for truck driving practice in military and civilian applications; to make recommendations to improve the use of time headway as a measure of driver performance safety and to identify some issues which merit further research.

The main body of the study is presented in detail in three supplements which are appended to this review. Supplements 1 and 2 originally constituted first and second Progress Reports respectively. Supplement 3 is an additional and final detailed report.

CONTENTS

Introduction

In a traffic situation where one vehicle is following another, time headway is the time it would take the following vehicle to reach the leading vehicle if the latter stopped dead. Under certain conditions this measure of driver performance may be unambiguously interpreted in terms of accident risk.

For any particular time headway sample, the driver of the following vehicle may be in any one of a number of different driving manoeuvres, for example, closing on the vehicle in front, braking, preparing to overtake or maintaining a constant following distance (steady-state following). Previous studies of the effects of prolonged driving on time headway have generally failed to distinguish between these different types of following manoeuvre. Yet it may be the case that time-driving has different effects on different manoeuvres and so one aim of this research was to explore that possibility.

A second aim of this research was to examine the relationship between speed and time headway in steady-state following. It has been suggested by Colbourn et al. (1978) that if drivers follow a leading vehicle at a distance that enables them to detect "drastic changes in the speed of that vehicle within a certain time interval" they will tend to follow too closely at higher speeds. Should the actual behaviour of drivers confirm this hypothesis, then a potentially vulnerable aspect of driver following performance will have been identified.

The raw data for this study were originally obtained in three field experiments which investigated the relationship between prolonged truck driving and time headway under normal driving conditions, in a continuous two-vehicle convoy and under conditions of unpredictable shift onset and duration. Details of these experiments are

comprehensively reported in Fuller (1983) and will therefore not be repeated here.

The main findings from this reanalysis of data, which took particular account of type of following manoeuvre, are reported in three parts below, with each part corresponding to one of the three supplements appended to the review. The first examines, under normal late-shift driving conditions, the effects of prolonged driving on time headway in four types of following manoeuvre. These were steady-state following, closing, braking and prior-to-overtaking.

The second part examines the effects of prolonged driving on time headway in three types of following manoeuvre, namely steady-state following, closing and braking-closing under a variety of different truck driving conditions. These consisted of normal driving, continuous two-vehicle convoy driving and two-vehicle convoy driving with unpredictable shift onset and duration.

The third part explores the relationship between vehicle speed and time headway in steady-state following and includes an examination of possible changes over time. This analysis was carried out for the data obtained under normal driving conditions and under continuous two-vehicle convoy driving.

The data, on which the results presented below are based, were obtained in more than 1,150 hours of truck driving in which the driver's time headway was continuously monitored and recorded. They provide a unique description of drivers' following performance over time and under a wide variety of experimental conditions.

Summary of results

Part 1 Normal late shift driving: effects of prolonged driving on time headway in manoeuvres of steady-state following, closing, braking and prior-to-overtaking (see Supplement 1 for details).

1. Different following manoeuvres are typically associated with a different mean time headway as presented in Table 1 below.

Table 1. Mean time headway for each following manoeuvre

Prior-to-overtaking	0.88 seconds
Steady-state following	1.89 "
Closing	2.15 "
Braking	2.82 "

2. The effects of prolonged driving on time headway vary depending on the following manoeuvre investigated.

(i) Steady-state following and closing - short headways are associated with periods of time during which the probability of sudden velocity decreases by the lead vehicle are relatively low (i.e. when driving on rural, open roads and when the driver is more familiar with the behaviour of the lead vehicle driver).

(ii) Braking - long headways are associated with the beginning and end of the driving shift. Taken together with subjective reports of increased drowsiness towards the end of the shift, this finding may imply that the safe control of deceleration when a leading vehicle slows down may be particularly sensi-

tive to a decrease in a driver's capability, requiring an increased margin of error to preserve safety under such conditions.

(iii) Prior-to-overtaking - no effect of prolonged driving was observed.

3. Time-related changes in a driver's following performance are indicative of adjustments to maintain safety rather than of increased risk. However the implication is there that if for some reason such adjustments are not made, following performance may be the more risky.

Part 2 Normal late shift driving, continuous two-vehicle convoy driving and two-vehicle convoy driving with unpredictable shift onset and duration: a comparison of the effects of prolonged driving on time headway in manoeuvres of steady-state following, closing and braking-closing (see Supplement 2 for details).

1. In all three kinds of driving conditions investigated, time headway very rarely shifts to a level below the recommended minimum of 1.5 seconds. Averaged over a period of time (30 or 60 min), driver's time headway is not unsafe.

2. No evidence was found, in any driving condition studied, for a progressive decrease in time headway to an unsafe level over prolonged periods of driving: what characterises the results are periods of time in which time headway is particularly long.

3. Periods of time in which time headway is particularly long are at the start of driving and at the end of driving, depending on the manoeuvre investigated. Time headway is particularly long at the start of driving for steady-state following,

closing and braking-closing manoeuvres. This finding may be interpreted as a warm-up or practice effect, an interpretation which is consistent with other evidence that mean time headway tended to be longest on the first day or two of each driver's 4 day schedule.

4. Time headway is particularly long at the <u>end</u> of driving for the braking-closing manoeuvre. This finding may reflect two important characteristics of the braking-closing manoeuvre in comparison with the other manoeuvres investigated, namely:
   a) it occurs in response to an imminent hazard (rear-end collision),
   b) it requires a relatively high level of control response.

5. The observation that drivers increase braking-closing time headway towards the end of prolonged driving implies that they are creating an enlarged safety margin. This may be in response to increases in feelings of exhaustion and drowsiness which drivers reported over the same time period.

<u>Part 3</u> The relationship between vehicle speed and time headway in steady-state following: normal and continuous two-vehicle convoy driving conditions.

1. Speed and time headway are inversely related: faster speeds are associated with a shorter time headway and vice-versa.

2. In relation to (1) above, drivers show a preference for a distance headway of around 70 feet. This is the headway at which an important cue in headway maintenance, the angular velocity of the lead vehicle, has its greatest influence.

3. Also in relation to (1) above, it seems likely that another important determinant of a driver's elected headway is the probability of his having to react to sudden deceleration by the lead vehicle, with short headways being associated with a low probability and vice-versa.

4. There is some evidence that at the end of a late shift (02.30 hrs finish) drivers follow more closely at high speeds. Coupled with evidence of the onset of feelings of fatigue and decreased motivation over the same time period, this <u>may</u> mean that drivers are less capable of dealing with sudden emergencies at this time. On the other hand it could be argued that, as a compensatory act, drivers shorten their time headway in order to drive up their declining arousal levels.

5. Individuals vary in the extent to which speed and time headway are related, even though the correlation is negative for all subjects. If one looks at the relationship between speed and following distance, although most subjects show a positive correlation, a few show a slight negative correlation: the faster they go, the shorter the following distance. Such individual differences may be related to accident propensity, although the evidence is not yet available to warrant such a conclusion.

A conceptual framework for vehicle following behaviour

From a behavioural point of view, the fundamental task for the driver is that of making avoidance responses to aversive stimuli (for example steering around a parked vehicle in the roadway; bringing the vehicle to a halt at a busy major intersection).

Because aversive stimuli in the road environment are usually preceded by discriminable other stimuli, drivers can make anticipatory avoidance responses to the aversive stimuli (for example the driver can imagine that, given his ongoing course or track, the parked vehicle in the roadway ahead constitutes a dangerous obstruction - his internal future projection can then act as a stimulus to trigger anticipatory steering movements; similarly major intersections ahead are usually preceded by a warning sign - the driver can begin to decelerate on discriminating this stimulus, even before he has visual confirmation of the actual hazard). Discriminative stimuli for aversive events need not originate primarily outside the driver. If he perceives a decrement in capability, perhaps because of drugs or sleep deprivation, this may mean that any attempt at manoeuvering a vehicle could be hazardous. The driver's own capability is part of the discriminative stimulus for aversive stimuli in the road environment.

One complication in the task confronting the driver is that, despite the presence of appropriate discriminative stimuli, the aversive stimulus simply may not arise: the warning signs (perhaps both literally and figuratively) are there for some impending hazard but the aversive stimulus is not realised (for example the parked vehicle ahead may suddenly drive away or off the roadway altogether; the major intersection may turn out to be devoid of all traffic).

This lack of total correspondence between discriminative stimuli and aversive stimuli in the road environment provides the driver with some flexibility in responding. If he ignores discriminative stimuli for aversive events (for whatever reason) the outcome need not be punitive because either the aversive event does not arise or if it does the driver may be able to make a delayed avoidance response to it (thus he may make a last-minute swerve around a parked car; or brake severely to a halt at the major intersection).

Aversive events in the traffic environment are not generally lying in wait to pounce upon the unwary motorist: they are frequently the result of the interaction between what the driver does and other features of the environment (thus an obstruction in the roadway or a major intersection are only aversive stimuli if the driver fails to make appropriate adjustments to his course or speed).

Because most aversive stimuli in the traffic environment arise out of this transaction between the road user and other features of the system, it is within the driver's capability to reduce their frequency to a very low level. He can do this, by and large, by making anticipatory complete-avoidance responses to the discriminative stimuli for aversive events, that is by making adjustments which negate or cancel out the anticipated aversive stimuli should they arise (for example by slowing into a blind corner so that if an obstruction should become evident the driver can stop safely or make some other safe avoidance response).

In terms of time efficiency, consistently making anticipatory complete-avoidance responses will generally not lead to the highest payoffs. This is because on occasion the anticipated aversive event does not arise or because even if it does, a delayed avoidance response can be made to deal with it. In the former case here, the anticipatory avoidanee response is in one sense not rewarded and therefore not reinforced.

Thus it is likely that other things being equal most drivers will opt for anticipatory partial-avoidance responses to discriminative stimuli for aversive events in the road environment. In other words, when anticipating the possibility of a hazard ahead, they will take some action to make coping with it that much easier or safer should the hazard actually arise. In this way, if the hazard (aversive stimulus) fails to materialise, the time cost (or course/speed adjustment cost) is reduced compared with that involved in an anticipatory complete-avoidance response: yet should a hazard arise it can be dealt with, albeit not with as wide a margin of safety as in the other case. It may be suggested that it is this compromise in driver behaviour which underlies a proportion of road traffic accidents: in particular where the partial-avoidance response is of a minimal kind. However in many accidents it may be clearly inferred that drivers have made no anticipatory avoidance response whatsoever, or have simply misread the available discriminative stimuli.

To consolidate what is being proposed here the reader is directed to the flow diagram in Figure 1. In essence it is suggested that aversive stimuli are generally preceded by discriminable other stimuli but the prediction from warning "signs" to hazards cannot be made with certainty: it is a question of subjective probability. Given a discriminative stimulus for an aversive stimulus a driver may make <u>no</u> anticipatory avoidance response. If he makes no response and no hazard arises, then he may proceed with impunity. If the hazard is realised however, then he must make a delayed avoidance response or experience the aversive stimulus itself (generally described as an accident).

If on the other hand he makes an anticipatory avoidance response, this may be either complete or partial. If the former then the effect is to negate the impending hazard and the driver may again proceed with impunity (usually

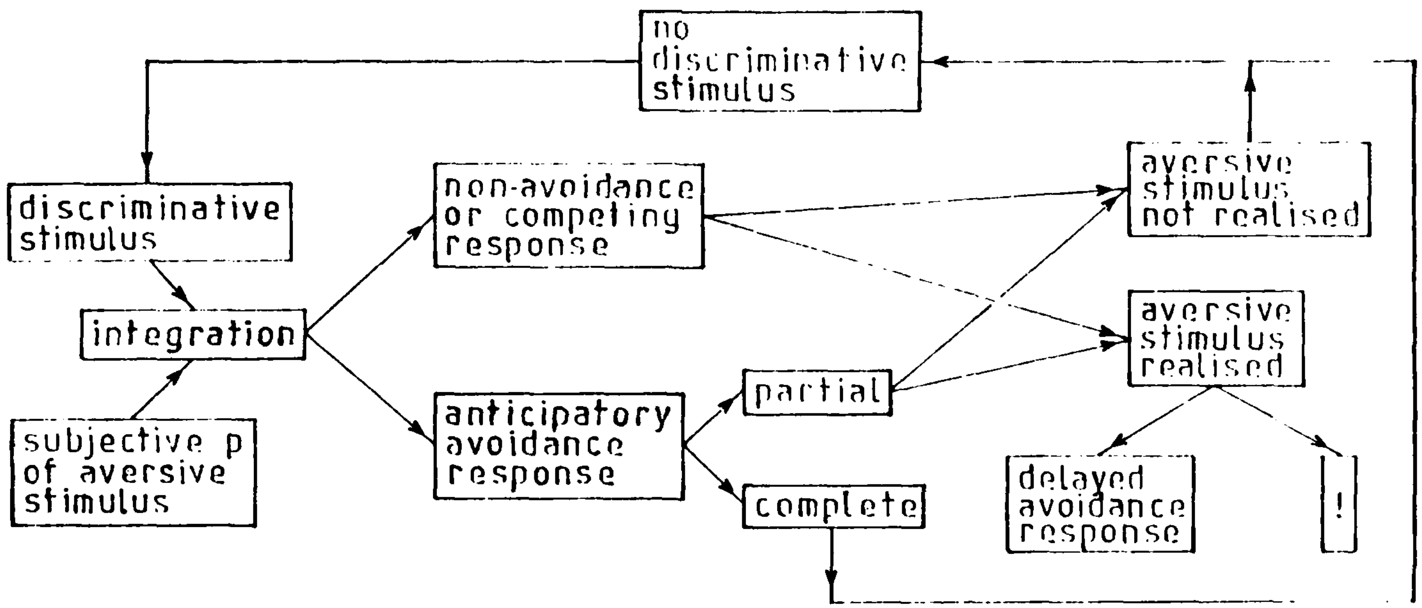

Figure 1. Outline behavioural model for driver behaviour.

whether or not the expected hazard actually arises). If an anticipatory partial-avoidance response is made however, given that the expected hazard does arise the outcome will depend on the adequacy of the partial-avoidance response to enable a safe and final delayed avoidance response.

A fuller development of this model is provided in Fuller (1984). However just to add one further and important point here, clearly from a behavioural perspective the kind of response a driver will make to a discriminative stimulus for an aversive event will depend in particular on (a) the subjective probability with which that event will occur and (b) the expected rewards and/or punishments for the various response alternatives.

Let us turn now to the particular driving task of vehicle following and the evidence in relation to that task which has arisen out of the studies described earlier.

A vehicle ahead which is following the same track as oneself constitutes a potential obstruction and is therefore a discriminative stimulus for the aversive event of a collision. A typical non-avoidance response to such a stimulus would be to catch up with it and follow as closely as possible, thereby having to make very severe braking or steering adjustments should the leading vehicle suddenly decelerate. An anticipatory complete-avoidance response would involve either overtaking or dropping far enough behind such that the leading vehicle no longer effectively shared the same track within the same time segment (i.e. could not be construed as a potential obstruction). It is perhaps worth noting here that this is in fact the preferred behaviour of most commercial vehicle drivers.

In convoy driving and periods during which following is unavoidable,however, such an anticipatory complete-avoidance response is not possible and the driver must therefore compromise with an anticipatory <u>partial</u>-avoidance

response. This will involve a range of behaviours such as attempting to anticipate leading vehicle deceleration (e.g. by looking out for approaching junctions and other hazards such as braking by vehicles ahead of the one being followed) and constant monitoring of relative velocity. However another important aspect of behaviour in this respect is the physical headway adopted by the driver: the interval that he attempts to maintain between himself and the vehicle in front. The longer this headway, the safer is the anticipatory partial-avoidance response made. This is because, should the leading vehicle decelerate, that much more time is available for the following driver to make an appropriate delayed avoidance response (of braking, swerving or whatever).

What factors have been shown in the results outlined earlier to be important in the determination of a driver's headway? The evidence from Part 1 demonstrates that drivers take account of the probability of leading vehicle deceleration, adopting a longer headway when this is relatively high (e.g. on urban roads) and a shorter headway when the probability is relatively low (e.g. on rural roads). In other words, in terms of the model outlined above, what drivers appear to be doing here is adopting a response which takes account of the subjective probability of an aversive stimulus arising, given the discriminative stimulus of a leading vehicle on the same course or track as themselves.

The period of driving on a shift was also found to be an important determinant of a driver's headway. In Part 1, increased braking time headway occurred at the <u>start</u> of driving and a similar effect was found for steady-state following, closing and braking-closing in Part 2. Increased braking time headway also occurred at the <u>end</u> of driving in both Parts 1 and 2 (specifically for braking-closing in Part 2). These results were interpreted to be due to the driver's assessment of variations in his ongoing <u>capability</u>, with the result that he adopted a longer headway when that

capability was perceived to be suboptimal (lack of practice and warm-up at onset of driving; increased drowsiness and exhaustion and decreased motivation at the end of driving). Thus in terms of the behavioural framework presented here, drivers may be said to be taking account of their ongoing capability in assessing the discriminative stimulus of the leading vehicle as one of potential threat, recognising this to be greater when their capability is lowered and therefore evoking a longer headway.

In addition to these anticipatory partial-avoidance responses, evidence for non-avoidance or competing responses in vehicle following was found in the analysis of the relationship between vehicle speed and time headway (Part 3). Given that other factors remain constant, in order to maintain a stable and safe time headway, as speed increases, drivers should progressively increase following distance. However it appears that drivers show a preference for a headway of around 70 feet, almost irrespective of their speed. Over a speed of about 32 mph this distance headway represents a time headway of less than 1.5s, the minimum headway recommended for drivers in the U.S. This response, therefore, is competing with the anticipatory avoidance response which would maintain time headway at or above the recommended minimum. Such a competing response is presumably reinforced by the facility with which headway changes can be detected at 70 feet distance, the distance at which the angular velocity of the leading vehicle has strongest influence.

Two other kinds of non-avoidance or competing response were also identified in the results of Part 3. One relates to the tendency for end-of-shift drivers to decrease distance headway at high speeds. It is suggested that the reinforcement for such a competing response may come from increased arousal arising from the threat engendered by the close proximity of a leading vehicle at high speeds. This arousal- increase may be rewarding in itself, but more

probably is one which enables the driver to complete his journey. It is a moot point, however, whether or not any arousal boost so obtained is effective in enhancing driver capability to such an extent that the additional riskiness of close following is compensated for.

The final kind of non-avoidance or competing response identified was one that was peculiar to a minority of drivers. These drivers were characterised by a general negative correlation between speed and distance headway: the faster they went, the shorter was their following distance. Again, if all other variables in the safety equation remain the same, the riskiness of this behaviour will progressively increase as the driver's time headway shrinks further and further below the 1.5s safety criterion. What is not clear in these drivers, however, is what kind of reward might be reinforcing the avoidance-competing response.

From the above discussion it may perhaps be seen that all of the main findings emanating from this study may be described within the framework of a behavioural analysis of the driving task. Figure 2 presents a brief summary of the findings, incorporated within that behavioural framework in the form of a flow diagram based on that of Figure 1. In sum it is argued that a main characteristic of driving is that of avoiding aversive stimuli. When following another vehicle, a decrease in the relative velocity of that vehicle constitutes the discriminative stimulus for a potentially aversive event. Drivers appear to make subjective judgements of the probability of such a threat or hazard arising and make anticipatory partial-avoidance responses or, under certain circumstances, non-avoidance or competing responses.

From the general viewpoint of the enhancement of driver safety, what we now really need to explore further are the conditions in which anticipatory avoidance and non-avoidance or competing responses are reinforced. Promotion of the former and elimination of the latter could well save lives and injuries and preserve physical resources.

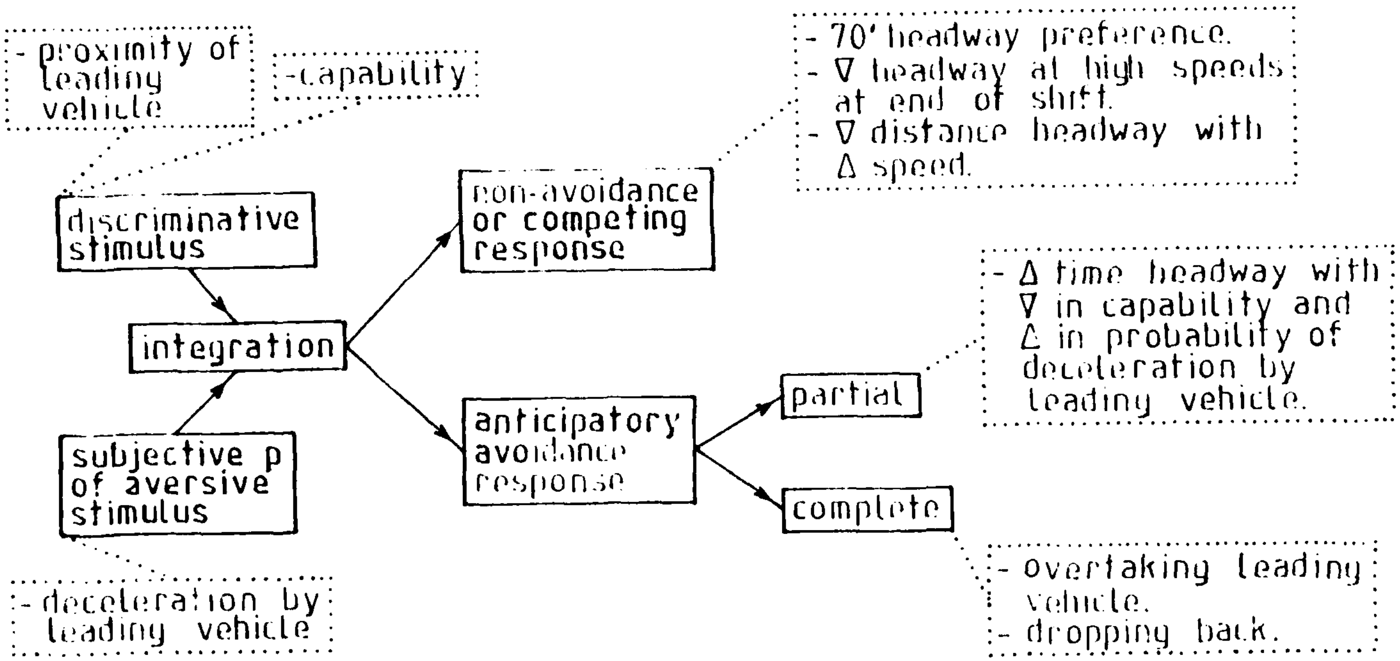

Figure 2. The principle results for time headway in different following manoeuvres mapped onto the behavioural model.

Implications for truck driving practice

1. Drivers appear to regulate their headway to take account of factors which raise or lower driving task demands (e.g. the likelihood of leading vehicle slowing, exhaustion and drowsiness, motivation, practice, visibility). Since such adjustments are safety oriented, drivers in convoy should be allowed flexible following distances.

2. There is some evidence that drivers prefer a 70 foot following distance. Such drivers should be alerted to the potential danger of this behaviour at speeds over about 35 mph, particularly where they cannot anticipate leading vehicle slowing.

3. Drivers differ in the kinds of headway adjustment they make when travelling at speed, some courting far more risk than others. To increase safety, drivers identified as risky followers should receive remedial training or be selected out of the pool of driving personnel.

Time headway as a measure of performance safety

Advantages

1. Time headway is a performance variable that can be easily monitored and recorded continuously, unobtrusively and accurately.
2. Time headway provides an integrated measure of the ongoing interaction between a driver, his vehicle and an important feature of the road environment (a potential forward obstruction).
3. Below a critical level, which may vary, time headway may be interpreted unambiguously in terms of collision potential, should the leading vehicle suddenly and unexpectedly decelerate.

Recommendations

Because the interpretation of the safety of any particular time headway value is a complex issue, the following procedural recommendations are made:

1. Discrete episodes of following should be analysed separately: averaging over time may obscure important variation.
2. Time headway is generally different in different types of following manoeuvre and the effects of important variables such as time-driving may not be independent of type of following manoeuvre. Therefore analysis of following performance should discriminate between different types of manoeuvre. Furthermore a less ambiguous interpretation of time headway data could be provided for the closing and perhaps also the prior-to-overtaking manoeuvre if the results for such manoeuvres were broken down into phases of onset, maintenance and termination.
3. Braking (and braking-closing) time headway appears to be an aspect of following performance which is particularly sensitive to factors which impair capability. Research exploring the effects of such factors might usefully pay heed to this observation.

4. Other factors remaining equal, a short time headway is not unsafe if the leading vehicle does not decelerate unexpectedly (assuming that headway is not so short that the following driver has no time to react and that the braking performance of the leading vehicle does not exceed that of the following vehicle). Therefore interpretation of time headway values should take account of features of the road traffic environment, in particular potential hazards or situations requiring vehicle deceleration. Relevant here are any features which obscure a clear view ahead (bends, bridges, rain, fog, tunnels) and other features such as junctions, crossings and pedestrians.
5. Interpretation of time headway values should also take account of the following driver's ability to stop in a controlled fashion should the leading vehicle decelerate. Consequently account should be taken of road surface conditions, the driver's competence in vehicle control (such as in skidding), the driver's ongoing capability (such as in sustained attention and reaction time) and the braking characteristics of the following vehicle relative to the leading vehicle.

Some issues for further research

1. Drivers conscious of another vehicle immediately behind them may momentarily defer adjusting their headway when there is a decrease in the relative velocity of a leading vehicle. This possibility is suggested to emphasise the point that the results of the research reported here are based mainly on a two-vehicle rather than a multi-vehicle convoy configuration. The latter merits separate investigation of its properties of driver stress, strain and performance breakdown as well as of the kinds of adjustment drivers may make under such convoy driving conditions.
2. The apparent preference for a 70 ($\pm$10) foot distance headway merits further examination. Two immediate questions pertain to the reliability of the phenomenon and the extent to which it occurs at driving speeds of over 50 mph.
3. There is much room for further work on individual differences in following behaviour. Can we talk about individual 'styles' of following? And if so, can these be related to accident propensity or be used in driver selection?
4. From a safety viewpoint it is worth exploring the extent to which close following at high speeds is used as a strategy to maintain or boost arousal. Should drivers adopt such a stragegy, does it lead to a net increase in accident riskiness?
5. In general, more emphasis could be placed on the identification of the rewards which reinforce both safe and dangerous driving. Greater understanding and control of the driver's reward system could well promote the safety of vehicle operations.

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Prolonged Heavy Vehicle Driving Performance: Analysis of Different Types of Following Manoeuvre

Supplement 1

SUMMARY

The results of an earlier study of the vehicle-following performance of truck drivers on a shift ending at 02.30 hr were reexamined by analysing separately the data for different types of following manoeuvre: steady-state, closing, braking and prior-to-overtaking.

No evidence of increased riskiness over time for any manoeuvre was found. Time headway prior to overtaking remained stable and time related changes in braking, closing and steady-state time headway appeared to reflect safe adjustments by the driver to changes in perceived characteristics of himself and the traffic environment.

These results were interpreted within the framework of a threat-avoidance model of driver behaviour. It was concluded that the ability to execute safe control of deceleration when confronted by a slowing leading vehicle may be especially vulnerable to prolonged driving effects. Consequently driving riskiness may be affected when appropriate compensatory adjustments are not made by the driver.

Truck driving in the early hours of the morning is associated with reports of increased drowsiness, decreases in competence and increased accidents (Fuller 1984). However studies of driver performance have generally failed to reveal reliable changes over time which may be unambiguously interpreted as increases in accident riskiness. In particular, in a study of the vehicle-following performance of truck drivers on a late shift which continued up to 02.30 hr (Fuller 1983) no clear effects of prolonged driving on performance safety were found.

Nevertheless it might be argued that one reason for finding no real evidence suggestive of performance decrement is that the performance measure used in that study, namely mean hourly time headway (TH) and its variability, was too gross a measure to reveal changes with important implications for safety. When one vehicle is following another, time headway is the time it takes the following vehicle to reach the leading vehicle if the latter stops dead. Although this measure of TH is under certain circumstances directly and unequivocally related to risk of collision, it has been shown to vary markedly as a function of the particular type of manoeuvre the following driver is engaged in (Fuller 1980). Thus measures of mean hourly TH, which incorporate all kinds of following manoeuvre, may conceal important interactions between type of manoeuvre and hours of driving.

The aim of this study, therefore, was to reanalyse the data of the earlier study of truck driver following performance, referred to above, by separating out for

analysis the results for four types of following manoeuvre:

(a) steady-state following (vehicles maintaining relatively constant TH in a 'coupled' state for 5s or more),

(b) closing (reducing distance to leading vehicle for a period of 5s or more, with no braking),

(c) prior-to-overtaking (immediately before overtaking manoeuvre initiated),

(d) braking (following vehicle brakes applied).

METHOD

The method for this experiment has been reported in full elsewhere (Fuller 1983). Consequently only those details relevant to the current reexamination of following performance data will be presented here.

Subjects. Subjects were six volunteer professional truck drivers, each paid $160 for participating in the study. Two different age groups were selected with mean ages 25.3 years (s.d. = 5.0) and 43.6 years (s.d. = 13.3) respectively.

Driving task. Each S was required to drive an instrumented 7-ton Bedford rigid van-type truck for 11 hours on each of four consecutive days over a preselected route of approximately 300 miles of main roads, repeated on each day. The route consisted of two different loops out of and returning to Dublin, the same loop being driven first on each day. The route as a whole was novel for the drivers although most of the roads involved were familiar to all of them. Driving was continuous except for a

3C min. meal break after 5.5 hours and one 5 min. break during each 5.5 hour session to refuel a petrol driven AC generator which powered the research instrumentation. All Ss drove a shift starting at 15.00 hours and ending at 02.30 hours.

Performance measures. The driving performance of interest was mean time headway for each hour of driving, with episodes of following separated into categories of steady-state following, closing, braking and prior-to-overtaking. Time headway was monitored for each manoeuvre using a closed-circuit television system described in Fuller, McDonald, Holahan and Bolger (1978).

Other measures. Systematically obtained were:

(a) daily records of Ss' sleep duration and quality, drug consumption and feelings prior to driving,

(b) self ratings of driving performance, motivation and fatigue for each hour of driving,

(c) daily pre-post samples of blood and urine for assay of five endocrine hormones.

'Contrived' following episodes. In an earlier study (Fuller 1978), it was found that after the third hour of driving on a late shift, identical to the one currently under investigation, the frequency of spontaneously arising following episodes was inadequate for reliable analysis. Thus from the fourth hour on additional following episodes were created by a second vehicle which intercepted the experimental truck at random points during each hour. The vehicle used was a 15 cwt. VW van, driven always by the same driver.

Following episodes were contrived by the leading vehicle appearing on the road well ahead of the truck and then permitting the latter to catch up. This procedure resulted in a 152% increase in the number of observations obtained of time headway compared with the same shift of the earlier study.

Instructions to S. With regard to the second vehicle, S was told that he would come across a white VW van driven by one of the research team at odd times during his shift and that he was to treat the van as he would any other vehicle on the road - the van was being used simply to increase the traffic density experienced by him.

At no point in the entire study was the driver informed that his following performance was under observation. The television cameras mounted in the truck were there "to record traffic conditions" and the main purpose of the study was "to explore the effects of prolonged driving on hormone secretion". In this way the unobtrusiveness of the time headway measurement was maintained.

Data sampling. Videorecords were obtained of all traffic situations in which the distance to a leading vehicle either decreased or remained stable. Sequences with TH $\geq$ 10s were excluded as not constituting true following episodes. Similarly excluded were situations in which the experimental truck approached a stopped, stopping or very slow front vehicle (as, for example, in a typical traffic jam or 'crawl'). The resulting

records of following episodes were sampled at a mean rate of once every 5s and the category of manoeuvre (steady-state, closing, braking, prior-to-overtaking), truck speed and distance headway values were transferred to record sheets for further analysis by an IBM 360 model 44 computer. Time headway means for each type of manoeuvre for each hour of driving were then obtained.

Statistical design. In conformity with previous studies by the author, the two 30 min. periods of driving in hour six, separated by a 30 min. meal break, were treated as separate levels of the 'Hour' factor in a factorial analysis of variance. It should be noted that the effect of this procedure is to weight equally the values for the separate halves of hour six with the values for each other whole hour. Thus the general design of the statistical analysis for each type of following manoeuvre was intended to be a 2x4x12 factorial analysis of variance with Age, Day and Hour as main factors, repeated measures on the last two factors and $n = 3$.

However because of the relatively small number of observations of following in the categories of closing, prior-to-overtaking and braking (see Table 2), for these manoeuvres data for age groups and days had to be combined to provide reliable samples. Thus for these categories of following, the statistical analysis was a single factor analysis of variance with repeated measures and $n = 6$, in which each S's mean hourly TH was based on his average for that hour over the four days of the experiment. Table 1 shows the

means for each age group and day associated with the three types of following manoeuvre. It may be seen that differences between groups and between days were invariably small.

RESULTS

Each driver in this study drove for approximately 44 hours. Of this time, about 4.8% was spent in some form of following manoeuvre, with steady-state following constituting by far and away the most frequent type of following (81%). As may be seen from Table 2, braking and closing manoeuvres accounted for similar proportions of following (9% and 8% respectively) whereas following prior-to-overtaking accounted for only 2% of all following.

Mean hourly TH was shortest for prior-to-overtaking episodes (0.88s), about one second longer on average for steady-state following (1.89s) and longer still for closing (2.15s) and braking (2.82s) (see Table 2).

Steady-state following. Of the 288 cells in the subjects x conditions matrix, 28 values (10%) were missing and these were subsequently estimated on the basis of each S's overall mean score. Degrees of freedom for the error variance in the factorial analysis of variance were correspondingly reduced by a factor of 28. The results of that analysis revealed no main effects of age or days and no interactions. However there was a significant main effect for hour ($F_{11,44} = 3.72$, $p < .01$). Hourly means are presented in Table 3 and graphically in Figure 1. The

critical mean difference was found to be 0.74s (where $t = 3.18$, $df = 44$, $p < .01$) indicating that steady-state TH for hour 5 was significantly shorter than for hours 3 and 4 (see Figure 1).

Inspection of Figure 1 suggests that although there was little overall change in steady-state TH, there was a slight decrease over time with two distinct periods of relatively short mean headway in hours 2 and 5. This pattern is virtually identical to that found in the earlier study (Fuller 1983) which combined results for the different types of following manoeuvre. Correspondence between the two sets of results is expected to the extent that steady-state following accounted for approximately 80% of all following.

<u>Closing</u>. Combining the data for age groups and days as described in the Method section yielded a subjects x hours matrix of 72 cells in which 5 cells (7%) were missing. Values for these were estimated on the basis of each <u>S</u>'s overall mean score and degrees of freedom in the error variance were correspondingly reduced.

The analysis of variance yielded a significant effect for hour ($F_{11,50} = 2.50$, $p < .05$) and the means for this effect are presented in Table 3. The critical mean difference was determined to be 0.87s (where $t = 2.51$, $df = 50$, $p < .05$). Thus mean closing TH for hour 1 was significantly longer than for hours 5 to 8, 10 and 11 and for hour 6 was reliably longer than for hour 5 (see graph in Figure 2). Longest closing TH was associated with

the beginning of each half of the driving shift and, as in the results for steady-state following, a relatively short TH was associated with hour 5.

Prior-to-overtaking. Because of the very small sample of following episodes which immediately preceeded an overtaking manoeuvre by the subject, the data for this category of following had to be combined for age groups and days, as for the data for the closing manoeuvre. However this still did not yield a reliable sample for every hour and so the data for each consecutive pair of hours were combined (i.e. hour 1 + hour 2, hour 3 + hour 4 etc) prior to further analysis. It should be noted that this procedure involved combining the data for hour 5 with the first half hour of data for hour 6 (i.e. before the meal break) and the data for hour 7 with the second half hour of data for hour 6.

No effect for hours (i.e. consecutive blocks of 2 hours) was found ($F_{5,22} = 1.04$, $p > .05$) and this result implies that drivers' headway prior-to-overtaking was relatively stable over time (see Figure 3). The means for this analysis are presented in Table 3.

Braking. Data for braking TH were combined in the same way as for closing TH described earlier. Thus the mean hourly TH for each S was determined on the basis of his average for that hour over the days for which reliable samples had been obtained (n max. = 4 days). Despite this procedure, data for hours 4 and 10 were still inadequate with only 33% of cells complete. These two hours alone

accounted for 36% of all missing data. Consequently they were excluded from further analysis. In the resulting analysis of variance, estimates had to be provided for only 5 cells (i.e. 8%) and were derived from the appropriate <u>S</u>'s overall mean score. The error variance degrees of freedom were correspondingly reduced.

A significant effect for hours was found ($F_{9,40} = 2.45$, $p < .05$) with the critical mean hourly difference being 0.82s (where $t = 2.51$, $df = 45$, $p < .05$). Thus, as can be seen from Table 3, hours 1 and 11, the first and last hours of driving, were associated with significantly longer braking TH than the intermediate hours 5 and 7. Furthermore braking TH for hour 9, the penultimate hour for which results were available, was reliably longer than for hour 7. This pattern of results may be seen more clearly in the graph of mean hourly braking TH, presented in Figure 4, in which the curve relating braking TH to time driving has a fairly distinct 'U' shape.

DISCUSSION

As noted elsewhere (Fuller 1980), time headway varies according to type of following manoeuvre. It is particularly short prior-to-overtaking (0.88s), next longest in steady-state following (1.89s), longer in closing (2.15s) and longest of all when braking (2.82s). This last value therefore represents positive deceleration relative to a leading vehicle when in a braking manoeuvre. Implications of the results for each of these manoeuvres <u>over time</u> will

be explored below within the framework of a descriptive model of driver behaviour, originally developed in Fuller (1983a) and revised in Fuller (1984a).

The model, represented schematically in Figure 5, construes the task of driving as essentially one of avoidance of potential aversive stimuli (i.e. threats). Given a *discriminative stimulus (sign, signal or simply* 'precursor') for a threat (in Figure 5, path from circles s, u, t to box a), a driver may make one of three types of avoidance response: non-avoidance (box e), partial anticipatory avoidance (box j) or complete anticipatory avoidance (box c). Which response he makes depends on his subjective probability of an expected threat (i.e. the degree of association between the discriminative stimulus or sign and the threat itself - circle v) and the rewards and punishments associated with each type of avoidance response to the particular discriminative stimulus in question.

It should be noted that discriminative stimuli usually arise out of some configuration of the road environment in conjunction with a fairly short forward-projection in the driver's imagination of his ongoing speed, path and capability. Thus an example of a discriminative stimulus might be a vehicle ahead, which in conjunction with the observing driver's speed and path would constitute an obstruction and therefore present a threat, requiring some form of avoidance response. Possible outcomes to the various forms of avoidance response may be traced in Figure 5 but will not be considered further here since they are not

of immediate relevance to this discussion. Additional details and analysis of the model may be found in Fuller (1984a).

Considering first the results for steady-state TH, two features of those results stand out in particular. One feature is the relatively short headway associated with hours 2 and 5 and the other is the apparent gradual decrease in headway over time. Because steady-state following accounts for about 80% of all following, it is perhaps not surprising that these results recapitulate those found earlier in an analysis of the aggregate ata, which pooled all types of following manoeuvre (Fuller 1983). It was suggested in that analysis, and may be suggested again here, that both features of the steady-state following results may represent a particular kind of adjustment by the driver, in which he is taking account of the likelihood of sudden velocity decreases by the leading vehicle, increasing headway when such decreases appear more probable.

In the terms of the threat-avoidance model, sudden velocity decreases by a leading vehicle constitute potential aversive stimuli (because of the associated possibility of rear-end collision etc.). Discriminative stimuli for such events arise out of configurations of the road environment in conjunction with the driver's path, speed and capability. Relevant aspects of the road environment in the situation under discussion would include the presence of requirements for the leading vehicle to slow down, such as junctions, traffic control devices, pedestrians and so on. Another

relevant component would be the degree of uncertainty associated with the driving behaviour of the leading vehicle driver (i.e. the reliability with which the following driver would predict sudden velocity decreases in the leading vehicle). Given these discriminative stimuli (indicating high probability of leading vehicle slowing down and/or uncertainty regarding same) the driver may make a partial avoidance response of increasing time headway, thus making a safe response possible should a sudden decrease in leading vehicle velocity actually occur (see path from partial avoidance response to delayed avoidance response in Figure 5).

In the steady-state following results, relatively long TH was associated with urban parts of the route in which velocity decreases by the leading vehicle were more probable and with that part of the shift when the behaviour of the leading vehicle driver was least predictable. Conversely relatively short TH was associated with those rural open-road parts of the route in which velocity decreases by the leading vehicle were highly unlikely (e.g., hours 2 and 5) and with those parts of the shift when the behaviour of the leading vehicle driver was relatively predictable (e.g., progressively from hour 3 after which proportionately more and more of following episodes were behind the VW van associated with the experiment). Under these conditions drivers could safely follow the leading vehicle more closely and an anticipatory

avoidance response of maintaining a longer headway was unnecessary.

The experimental design of this study does not, of course, constitute a test of the threat-avoidance hypothesis implicit in the model. The model is simply used here to provide a conceptual framework for interpreting the results of the study. The observed progressive decreases in steady-state TH over time, for example, could also be interpreted as representing a progressive increase in riskiness, particularly if account is taken of drivers' subjective reports of drowsiness, which were significantly correlated with driving time (see Fuller 1983). Even constant headways over time could represent increasing riskiness if driver competence (for example to respond rapidly) was simultaneously decreasing. Nevertheless it should be borne in mind that even at its shortest mean value, steady-state TH did not exceed the U.S. recommended minimum of 1.5s (2.0s in U.K. and Ireland). Furthermore other time headway evidence supportive of a threat-avoidance interpretation has been reported by Forbes (1959) who found that U.S. drivers adopted longer headways when entering tunnels and further increased headway when negotiating right curves, downgrades and low illumination levels (and see also Fuller 1981).

Mean time headway for closing manoeuvres provides an estimate for each hour of driving of following intervals prior to the threshold at which drivers adopt steady-state following. Not surprisingly, the pattern over time

for closing TH found here reflects that found for steady-state TH, with features of a relatively short mean TH in hour 5 and an otherwise gradual decrease in TH as the shift progressed. Just as for steady-state TH, this pattern may be construed as representing headway adjustments which take into account the likelihood of sudden velocity decreases by the leading vehicle (see discussion above). It should be noted however that the measure of closing TH used in this study integrates three different variables associated with the closing manoeuvre: the headway at which the manoeuvre is initiated; the duration of the manoeuvre until steady-state following is established; the threshold at which steady-state following is established. It is suggested that future studies of driver following performance might more profitably separate out for analysis these three components of closing manoeuvre onset, duration and termination.

In contrast to the results for steady-state and closing TH, the results for TH prior-to-overtaking, although based on a relatively small sample, indicate no change over time whatsoever. Prolonged driving does not appear to make onset of the overtaking manoeuvre more risky, for example by the driver following more closely. Nor does it appear that prolonged driving requires the kind of adjustment in which the driver initiates the overtaking manoeuvre from further behind the leading vehicle (which would, of course, yield an increase in TH prior-to-overtaking). Unless it is assumed that driver competence is unstable, and in

particular that it may deteriorate over time, riskiness in instigating overtaking appears to be relatively constant.

Finally, the pattern of time headway means for the braking manoeuvre appears to be unique, relative to the other manoeuvres investigated, being characterised by a fairly distinct 'U' shape: shorter headways are clearly associated with the middle of the shift and longer headways with its beginning and end (see Figure 4).

Longer, and therefore safer, headways have already been observed in closing and steady-state following manoeuvres during the early phases of the driving shift. These long headways may be attributed to the driver's perception of an increased probability of potential aversive stimuli arising during this period because of (a) a relatively high probability of sudden deceleration by the leading vehicle, (b) uncertainty regarding the braking behaviour of the leading vehicle and one might add (c) lack of practice (i.e. reduced competence prior to 'warm up'). The distinctive feature of the results for braking TH, however, is the large increase in mean headway seen towards the end of the shift. Taking into account drivers' ratings of drowsiness, which showed reliable increases over time, the adjustment in headway may be construed as a compensatory response, motivated by a perceived decrease in capability.

Thus reviewing this result within the framework of the threat-avoidance model, increased braking TH may be said to represent a partial avoidance response to the discriminative stimulus (for threat) arising out of the

driver's perception of particular features of the traffic environment (early part of the shift) and also of his changing capability (early and later parts of the shift).

Conclusion. This entire reanalysis of data from an earlier experiment was undertaken to determine whether or not there existed interactions between hours of driving and time headway adopted in different types of following manoeuvre which might have implications for driver riskiness and road safety. From these results it has to be concluded that although time-driving has different effects on time headway in different following manoeuvres, there are few, if any, implications of increased riskiness. No effect of hours on time headway prior-to-overtaking was found at all. Time related changes in braking TH, which invariably represented a positive deceleration relative to the leading vehicle, were more consistent with an interpretation of compensatory adjustment to maintain safety. Changes in steady-state and closing TH similarly seemed to reflect safe adjustments by the driver to changes in perceived characteristics of the task rather than anything else.

Nevertheless this general conclusion rests to an extent on the assumption that, during the 11 hour driving session, the capability of drivers did not deteriorate. Relatively short headways, for example, may be safe while the driver is alert and active but risky if he should become distracted or begin to fall asleep. The assumption that driver capability did not deteriorate is not consistent

with subjective reports of feelings of drowsiness, nor is it consistent with what appears to be a compensatory response in braking performance over the last hours of the shift.

The conflict can be resolved, however, if it is allowed that different aspects of following performance may be differentially sensitive to the effects of prolonged driving (perhaps in terms of the time-scale of effects). Thus although 11 hours of driving does not seem to affect initiation of overtaking, closing manoeuvres or steady-state following, the safe control of deceleration when confronted by a slowing leading vehicle may be especially vulnerable. Hence some form of compensation such as earlier braking (represented by the observed increase in braking TH) is adopted by the driver to allow for a greater margin of error. If this kind of avoidance response _is_ really necessary as an adjustment by the 'fatigued' driver, then driving riskiness will be affected when either the adjustment is not large enough, or for some reason is not made at all.

Table 1. TH means for closing, prior-to-overtaking and braking by age group and day (seconds)

	Young	Old	Day 1	Day 2	Day 3	Day 4
Closing	2.1	2.2	2.1	2.3	2.1	2.1
Prior-to-overtaking	0.8	0.9	1.0	0.8	1.0	0.9
Braking	2.8	2.9	3.0	2.9	2.8	2.7

Table 2. Following manoeuvres: distribution and mean TH

	% of all driving	% of all following	mean TH	sd
Steady-state	3.9	81	1.89	0.22
Braking	0.4	9	2.82	0.63
Closing	0.4	8	2.15	0.67
Prior-to-overtaking	0.1	2	0.88	0.22

Table 3. Mean hourly TH for each category of following (seconds)

	Hour											
	1	2	3	4	5	6_i	6_{ii}	7	8	9	10	11
Steady-state	2.1	1.7	2.2	2.2	1.5	2.0	1.9	1.8	1.9	1.8	1.6	1.7
Closing	3.0	2.3	2.3	2.3	1.4	2.1	2.5	2.0	2.1	2.2	1.8	1.9
Prior-to-overtaking	-1.0-		-0.9-		-0.7-		-1.0-		-0.8-		-0.9-	
Braking	3.4	2.8	2.8	-	2.5	2.7	2.9	2.3	3.0	3.1	-	3.3

Figure 1. Steady-state Time headway.

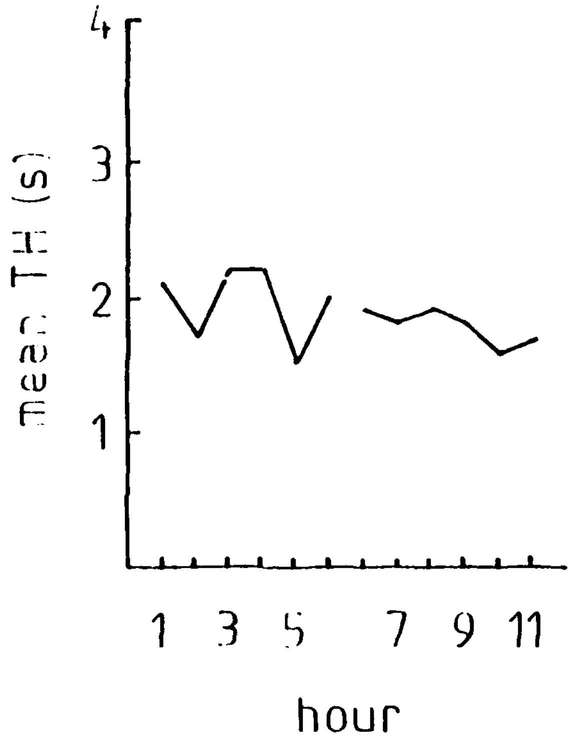


Figure 2. Closing Time headway.

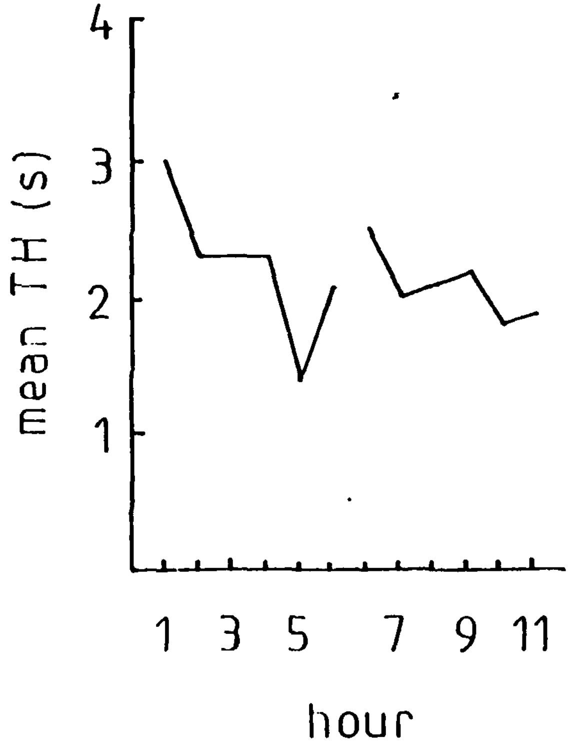


Figure 3. Prior-to-overtaking Time headway.

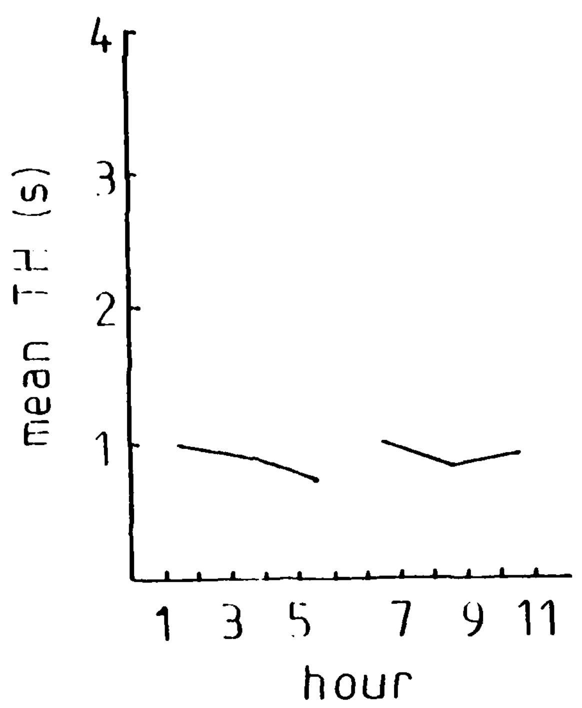
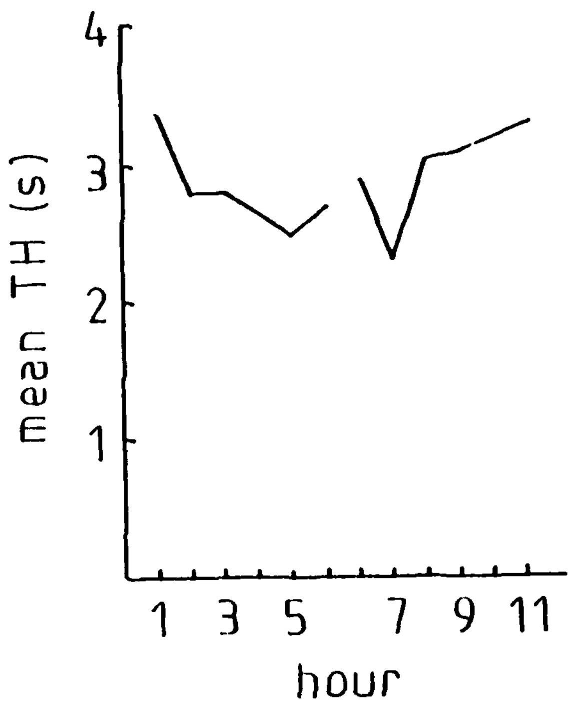


Figure 4. Braking Time headway.



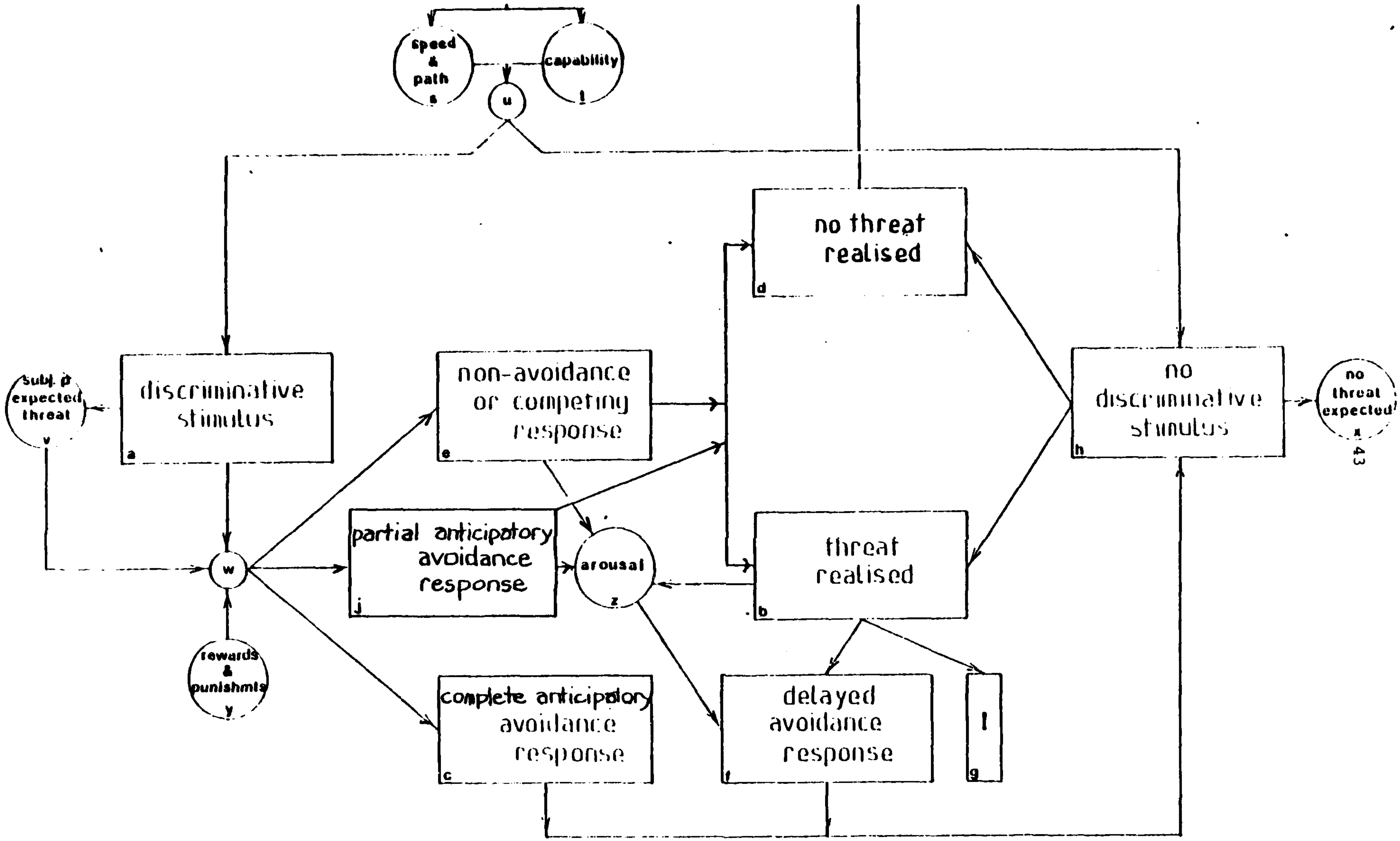


Figure 5. Threat-avoidance model of driver behaviour.

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Prolonged Heavy Vehicle Driving Performance:
Analysis of Different Types of Following Manoeuvre

Supplement 2

Summary

The effects of prolonged driving on time headway in steady-state following, closing and braking-closing were examined in three field experiments. The first of these involved truck driving under quasi-normal driving conditions, the other two involved truck driving in a two-vehicle convoy.

No periods of excessively short headways were found but what characterised the results were periods in which drivers opted for particularly long headways. In all three experiments, and for all types of manoeuvre investigated, drivers had relatively long time headway when they started driving. For the braking-closing manoeuvre they also had a relatively long time headway at the end of driving.

It was proposed that drivers opt for extended headway when some factor is interfering with their capability to follow more closely. Thus lack-of-practice might account for early long headway whereas exhaustion, coupled with drowsiness, might account for the late long headway.

Evidence was brought forward in support of these hypotheses. It was concluded that truck drivers do not operate with dangerously short headways over periods of time; that when they experience difficulties they increase headway; that these difficulties appear to be greater at the beginning of driving than at the end (even of prolonged periods of driving) and that the braking-closing manoeuvre is particularly sensitive to factors which undermine the driver's capability. It was suggested that this is because, in the braking-closing manoeuvre, there is a requirement for a fairly high level of skill for safe avoidance of an impending hazard.

When one vehicle is following behind another, the time headway (TH) of the second vehicle represents the time it would take that vehicle to run into the leading vehicle should it suddenly stop dead. Other things being equal, the shorter this TH interval the more risky is the driving situation. This is simply because if the vehicle in front suddenly and rapidly decelerates the driver of the following vehicle has less time to avoid collision.

The relationship between prolonged truck driving and variations in this time headway variable has been explored in a number of experimental studies in-the-field. These differed in the tasks required of drivers, ranging from quasi-normal driving (Fuller 1983) to continuous following in a two-vehicle convoy (Fuller 1980a, 1981) and convoy driving under conditions of unpredictable shift onset and duration (Fuller 1983). The overall results of these three studies have been compared in an earlier report (see Fuller 1983).

Episodes of following behind another vehicle are not all equivalent and may be classified into different types of following manoeuvre such as closing on the vehicle in front, preparing to overtake and braking, as well as the more prevalent condition of steady-state following (both vehicles in a 'coupled' state). A preliminary analysis of these different types of following manoeuvre revealed that TH is typically different for each (Fuller 1980b). Consequently the aim of this report is to compare the three studies indicated above, reviewing again the effects of prolonged driving on TH, but in three discrete types of following manoeuvre.

Following manoeuvres. The types of following manoeuvre investigated in this review were determined by the nature of the data available from the three studies in question and were as follows:

(a) steady-state following - where vehicles maintain a relatively constant TH in a 'coupled' state for 5s or more,

(b) closing - where the following vehicle progressively reduces distance to the leading vehicle for a period of 5s or more, with no braking,

(c) braking-closing - where the following vehicle's brakes are applied whilst simultaneously closing on the vehicle in front.

It should be noted that both experimental field studies which involved driving in convoy made a distinction between two types of braking manoeuvre: braking when closing (braking-closing) and braking whilst maintaining a relatively constant distance headway. It was found in both studies, and most particularly in the last (unpredictable shift onset and duration) that by far and away the largest proportion of braking episodes occurred as the following vehicle was closing on the leading vehicle. Indeed in the first convoy study the proportion of other braking constituted only 1.7% of all following and in the last study was so small it was considered inadequate for analysis. Consequently only the braking-closing results for these studies are considered here. Unfortunately the data of the study of normal following did not discriminate between types of braking manoeuvre and included both. However it may be assumed that recorded TH values would be weighted strongly towards braking-closing and would be reasonably representative of that manoeuvre.

Differences between the three experiments. Detailed descriptions of the design, method and procedure of the three experiments may be found in Fuller (1980a, 1981 and 1983). Important differences between them in driving task requirements are described in Table 1. In most other respects the three experiments were similar. Thus in all three studies volunteer professional (commercial or army) truck drivers were employed and each paid approximately $160 for participating. All subjects drove the same instrumented 7-ton Bedford rigid van-type truck for 4 consecutive days, mainly over trunk roads and within a radius of 150 miles of Dublin. There were 6 drivers in the first experiment (normal following) and 12 in each of the other two.

All subjects were fully informed about onset and duration of each driving period except for half of the subjects in the last experiment (unpredictable shift onset and duration). However since no main effect of the information variable was found on the TH results, this difference may be discounted.

There were two age groups of subjects in the normal following experiment (mean ages 25.3 yr and 43.6 yr) and the first convoy experiment (mean ages 22.7 yr and 33.5 yr) but only one age group in the second convoy experiment (mean age 27.8 yr). In all other main respects, such as use of unobtrusive TH recording techniques and the range and type of additional measures taken, the three experiments were essentially the same.

Comparison of the results of the three studies

General. The proportion of time spent in each of the different following manoeuvres in each study is presented

in Table 2. The column heading 'Convoy 2' in that table refers to the third experiment in which half of the subjects operated under a condition of unpredictable onset and duration of the driving task. For brevity of exposition, the label 'Convoy 2' for that experiment will be retained for the remainder of this report.

It may be seen from Table 2 that in all experiments the largest proportion of following manoeuvres is constituted by steady-state following and that the overall distribution of the different manoeuvres is very similar for Normal following and Convoy 1. However in Convoy 2, although the proportion of braking-closing manoeuvres remains small and roughly equivalent to that found in the other studies, there is a distinct increase in the proportion of closing manoeuvres and a corresponding decrease in that for steady-state following ($X^2 = 39.1$, df = 2, $p < .01$). One might speculate that this difference could be caused by a disproportionate increase of closing manoeuvres in the uninformed condition of that experiment, created by uncertain drivers 'chasing' the leading vehicle so as not to lose it on the route. However, examination of the data revealed no differences whatsoever between uninformed and informed driving conditions. One is forced to conclude that the difference between Convoy 2 and the other studies in the proportion of closing manoeuvres must be attributable to the different driving conditions of that experiment. These involved following a saloon car (rather than a 15 cwt van), a large number of discrete driving periods (rather than a small number of long driving periods), considerable variation in duration of driving periods (rather than constant duration) and a

continuously changing route (rather than the same route driven each day). However, which is the important factor(s) here is anyone's guess.

Table 3 presents the mean periodic (hour or half-hour) TH for each following manoeuvre. The main features of note here are the lack of evidence for any periods of dangerously close following and the statistically reliable finding of a longer TH associated with the braking-closing manoeuvre compared with the other manoeuvres, a finding common to all three studies. What this second result means is that when closing on the vehicle in front and simultaneously braking, drivers are decelerating positively relative to the leading vehicle. Thus when the vehicle in front is getting physically closer, drivers are actually creating a safer time headway.

Steady-state following. Time headway means for the steady-state following condition are presented in Table 4 and graphically in Figure 1 (values for the two halves of hour 6 in Normal following and of each hour in Convoy 2 have been combined in all figures). Statistically reliable comparisons were that under conditions of Normal following, TH for hour 5 was less than for hours 3 and 4; in Convoy 1, TH for hour 1 was greater than for all other hours and late shift TH was greater than early shift TH; in Convoy 2, TH was generally greater at the end of the 18 period schedule (i.e. 9 hours driving over a span of 10-11 hours - note that in Convoy 2 drivers drove daily schedules of 6, 7, 8 or 9 hours). It was also found in Convoy 2 that TH was greater at the start of driving on the first two days.

In general, as may be seen from Figure 1, these results

show that slightly longer headways are associated in particular with the onset of driving. A marked increase in TH in the last hour of the 9 hour driving schedule of Convoy 2 diverges from the other results.

Closing. Means for closing TH are presented in Table 4 and graphically in Figure 2. It may be seen that, with one or two exceptions, the pattern of change over time resembles that for steady-state following. Statistically significant results for Normal following were that TH in hour 1 was greater than in hours 5 to 8, 10 and 11 and TH in hour 5 was less than in 6_{ii}; for Convoy 1, TH in hour 1 was greater than in all other hours (most reliably evident in younger drivers). There was also a significant 3-way interaction showing that younger drivers on the late shift had longer headways at the start of the experiment. For Convoy 2, in all schedule lengths (i.e. 6, 7, 8 or 9 hours of driving), TH was greater in the first half hour compared with most other periods. There was an apparent trend towards increased TH at the end of the longer schedules (8 or 9 hours) but the changes involved did not reach statistical significance.

In sum, as with steady-state following, longer headways in the closing manoeuvre are associated with the start of driving on each day.

Braking-closing. Means for braking-closing TH are presented in Table 4 and reproduced graphically in Figure 3. On this dimension of following performance, much greater correspondenc between the three experimental studies may be seen, with relatively long headways characterising the early and late parts of the driving shift in each study. Significant

results for Normal following were that TH in hours 1 and 11 was greater than in hours 5 and 7, and in hour 9 (the penultimate period for which reliable data were available) TH was greater than in hour 7. In Convoy 1, TH for hour 1 was greater than for hours 2 to 8 inclusive; for hour 11 was greater than for hours 5 and 8 (an effect mainly characteristic of older drivers on the late shift) and late shift TH was greater than early shift TH. Lastly in Convoy 2, for the three shorter schedules (6, 7 and 8 hours), TH for the first half-hour period was greater than for most other periods. In the 9 hour schedule it was significantly greater than for periods 6, 9, 10 and 16. Time headway in the last period was greater than in period 8 for the 8 hour schedule and in period 12 was greater than in periods 5 to 11 and 14 to 16 for the 9 hour schedule.

Thus overall in the results for braking-closing there is a fairly distinct pattern, common to all three studies, of a U-shaped curve relating TH to time driving. The reliability of the 'end' effect in the Convoy 2 study is not as high as it might have been, but nevertheless a similar and consistent trend may be discerned over the last three periods for all but the 9 hour schedule in that study.

For convenience, Table 5 summarises all of the statistically reliable results obtained for the three experiments and three types of following manoeuvre described above.

Discussion

The studies reviewed here involved more than 1,150 hours of truck driving during which time headway was continuously monitored. Examining the results for signs of increased

riskiness by drivers, revealed by periods of short time headway, one is led to the conclusion that there is very little evidence for it. With the exception of only three instances no half-hourly and no hourly TH value dropped below the recommended U.S. minimum of 1.5s. All of these instances occurred in Convoy 1 and for the relatively safe manoeuvre of closing (see later), with two values of 1.4s and one of 1.3s. Furthermore there was no evidence, under any condition, of progressive decreases in TH to an unsafe level, particularly after prolonged periods of driving. What characterises the results is that there were periods of time during which TH was especially long.

For the driver, close following involves, amongst other things, being alert to sudden and rapid decreases in leading vehicle speed which require an immediate and controlled response. Should the driver's ability to do this be impaired in some way (for whatever cause), one simple expedient would be to increase time headway, thereby providing more time in which to respond, should the leading vehicle suddenly slow down. On this view a long headway may be interpreted as a form of compensatory adjustment by the driver. It assumes, of course, that the driver's motivation to follow closely (i.e. at a 'normal' distance) remains constant.

For all types of manoeuvre investigated, drivers had relatively long TH at the start of driving and, for the braking-closing manoeuvre, a long TH at the end of driving. This pattern of long headways was typical of all three experiments, despite their different conditions, although there were one or two deviations such as the terminal steady-state TH in the long schedule of Convoy 2 (see Figure 1).

The general pattern of results may be seen highlighted in the data of Table 6 which combines the results for all experiments and shows the percentage increase in TH in the first and last driving periods of the shift compared with the mean TH for all intervening periods. It may be noted that in the last period of steady-state following and closing the TH increase was only of the order of 3% whereas for braking-closing it reached 24%.

What kind of factor might interfere with the driver's optimal functioning at the start of the driving day and cause him to increase his TH in compensation? Perhaps the most likely candidate here is lack of practice. It is a well established observation that practice can improve performance at psychomotor tasks both as a 'warm-up' effect and as a learning experience. Perhaps the early decrease in TH from a relatively high level on each day reflects such an effect. The various changes observed <u>over</u> days and itemised below are also consistent with this 'practice' hypothesis:

(a) in Convoy 1, closing TH was longest on the first day,

(b) in Convoy 2, significantly longer steady-state TH was characteristic of the first two days only,

(c) in Convoy 2, longest braking-closing TH was found on the first day.

If early periods of driving are associated with a long TH because of lack of practice, what factor or factors might require a long TH at the end of the working day? Obvious possible candidates here would include:

(a) exhaustion from prolonged driving: in Normal following,

Convoy 1 and some of the schedules in Convoy 2, the end of the driving day occurred after unusually prolonged periods of driving which for two of the studies involved continuous following in convoy. Consistent with the 'exhaustion' hypothesis is the observation that towards the end of the shift drivers generally indicated decreased motivation to continue driving (see Fuller 1983 for details),

(b) drowsiness from lack of sleep (and perhaps induced low arousal): in Normal following and Convoy 1, drivers were still on the road when they would normally have been asleep. Consistent with this 'drowsiness' hypothesis are the reported feelings of drivers of increased drowsiness over the last few hours of driving (see Fuller 1983, 1984).

However, assuming the validity of these suggestions, it still remains to be explained why prolonged periods of driving should require adjustments in braking-closing TH but not generally in the other manoeuvres (the exception being steady-state following under the conditions of Convoy 2). Several features characterise the braking-closing manoeuvre which perhaps account for its particular sensitivit to factors which undermine driver capability.

But first consider steady-state following and closing. In the former the driver is in a relatively <u>stable</u> traffic situation, usually maintaining a constant speed which matches that of the leading vehicle. In the closing manoeuvre, the driver is typically trying to catch up with the leading vehicle having temporarily fallen too far behind. In neither

of these two manoeuvres does the ongoing traffic situation constitute an immediate threat to the following driver.

On the other hand when braking-closing, what the following driver is usually responding to is a dynamic and threatening change in the traffic situation, one which involves a decrease in speed of the leading vehicle which is so significant that it cannot simply be accommodated by easing up on the gas pedal alone. In this situation the behaviour of the leading vehicle may constitute a real threat, the avoidance of which requires the following driver to detect changes in relative rates of deceleration and execute appropriate control responses rapidly. It is this proximity to some potentially aversive consequence, coupled with the requirement of a fairly high level of skill for safe avoidance (and frequently a restricted range of response alternatives) which distinguishes the braking-closing manoeuvre from the other manoeuvres examined. For these reasons the braking-closing manoeuvre may be more sensitive to factors which impair ongoing capability, resulting in a relatively marked increase in time headway. Drivers thus appear to put up the greatest defense precisely where they feel most vulnerable.

One final observation may be made which is entirely consistent with this general compensatory-adjustment interpretation of changes in time headway. The task of close-following another vehicle in darkness is, not surprisingly, more difficult than in daylight because of reduced visual information about vehicle speed and distances. In Convoy 1, about 80% of the late shift was driven at night in darkness. In that condition drivers reliably increased time headway in all three following manoeuvres.

Conclusions

1. Truck drivers do not respond to the demands of the tasks imposed on them in these studies by driving more dangerously.
2. They adjust by adopting a safer following distance, thereby exploiting the essentially self-paced nature of the driving task.
3. By implication, the demands of close following appear to be greater when the driver initially sets out than after prolonged periods of driving (long headways are more pervasive then).
4. If very close following is a task requirement, as might arise in some military contexts, the observed safe-following adjustment (2 above) would be made at the expense of effectiveness in initial periods of driving. Little effectiveness would be lost after prolonged driving, however, because of the small amount of time spent in the braking-closing manoeuvre.
5. By implication, the braking-closing manoeuvre appears to be particularly sensitive to factors which detract from a driver's full capability. It could perhaps be developed as an indicator of changes in task demands on the driver.

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Table 1. Experimental differences in task requirements

	Experiment 1	Experiment 2	Experiment 3
Type of task	Normal following	Continuous convoy	Continuous convoy, with unpredictable task onset and duration for half of subjects
Shift onset	One shift: 15.00-02.30	Two shifts: 09.00-20.30, 15.00-02.30	Varying: 09.00, 10.00, 11.00 or 12.00
Duration of driving	11 hours daily, continuous except for 30 min. meal break and 2 x 10 min. fuel stops	As for Expt. 1	6, 7, 8 or 9 hours. Driving time in periods as follows: 7x1 hr, 4x2 hr, 2x3 hr, 1x4 hr, 1x5 hr, spread over 4 days. 30 min. break between periods
Driving span	11.5 hours	11.5 hours	6.5-11.0 hours
Route	Same each day	Same each day	Different each day
Distance	300 mi. per day	300 mi. per day	180-270 mi. per day
Leading vehicle	Spontaneously arising on roadway but incl. white 15 cwt VW van from 4th hour on, creating 80% of all following	Continuous white 15 cwt VW van	Continuous blue Renault 4 saloon

Table 2. Proportion of time in different following manoeuvres as percent of all following

	Normal following	Convoy 1	Convoy 2
Steady-state	81	82	51
Closing	8	13	41
Braking-closing	9*	3	7

*estimated maximum.

Table 3. Mean time headway for different following manoeuvres (in seconds)

	Normal following	Convoy 1		Convoy 2
	Late shift	Early shift	Late shift	
Steady-state	1.89	1.57	1.86	2.10
Closing	2.15	1.50	1.77	2.00
Braking-closing	2.82	2.28	3.21	2.95

Table 4. Time headway means for each sample period

Experiment 1: Normal following

	hour											
	1	2	3	4	5	6_i	6_{ii}	7	8	9	10	11
Steady-state	2.1	1.7	2.2	2.2	1.5	2.0	1.9	1.8	1.9	1.8	1.6	1.7
Closing	3.0	2.3	2.3	2.3	1.4	2.1	2.5	2.0	2.1	2.2	1.8	1.9
Braking	3.4	2.8	2.8	-	2.5	2.7	2.9	2.3	3.0	3.1	-	3.3

Experiment 2: Convoy 1

	hour										
	1	2	3	4	5	6	7	8	9	10	11
Steady-state	2.2	1.5	1.6	1.7	1.6	1.7	1.5	1.7	1.6	1.7	1.7
Closing	2.6	1.4	1.5	1.6	1.4	1.8	1.3	1.5	1.5	1.6	1.6
Braking-closing	3.6	2.4	2.4	2.4	2.2	2.5	2.5	2.2	2.9	2.6	3.4

Experiment 3: Convoy 2

	half-hour										
	1	2	3	4	5	6	7	8	9	10	11
Steady-state	2.4	2.2	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.1	2.1
Closing	3.1	2.3	1.9	1.8	1.8	1.9	1.9	1.8	1.9	1.9	2.0
Braking-closing	4.7	3.4	3.4	3.1	2.2	2.6	2.5	2.7	2.5	2.5	2.7
	12	13	14	15	16	17	18				
Steady-state	2.1	2.1	2.1	2.0	2.1	2.4	3.4				
Closing	1.9	2.0	1.9	2.0	2.1	2.3	2.4				
Braking-closing	3.3	3.1	2.7	2.8	3.1	3.7	3.0				

Table 5. Significant time headway results for each following manoeuvre

	Normal following	Convoy 1	Convoy 2*
Steady-state	hour 5<3&4	hour 1> all other late> early shift	period 1> most other (day 1 and 2 only, schedules pooled) period 18> most other (p<0.1)
Closing	hour 1>5-8,10,11 hour 6_i>5	hour 1> all other (not as reliable in older drivers) late>early shift young>old day 1>2&4 (mainly young drivers on late shift)	period 1> most other (all schedules)
Braking-closing	hour 1&11>5&7 hour 9>7	hour 1>2-8 hour 11>5,8 (mainly older drivers on late shift) late>early shift	period 1> most other (schedules 12,14&16 -for schedule 18, period 1> 6,9,10,16) period 16>8 (schedule 16) period 12>5-11, 14-16 (schedule 18) day 1> all other (schedules pooled)

*'period' represents a half-hour period of driving; different schedules are designated by the number of periods spent driving in each (e.g. schedule 18=18x0.5 hours or 9 hours driving)

Table 6. Percentage increase in time headway for first and last driving periods compared with mean for intervening samples

	First period	Last period
Steady-state	21	3
Closing	60	3
Braking-closing	46	24

Figure 1 STEADY STATE TIME HEADWAY

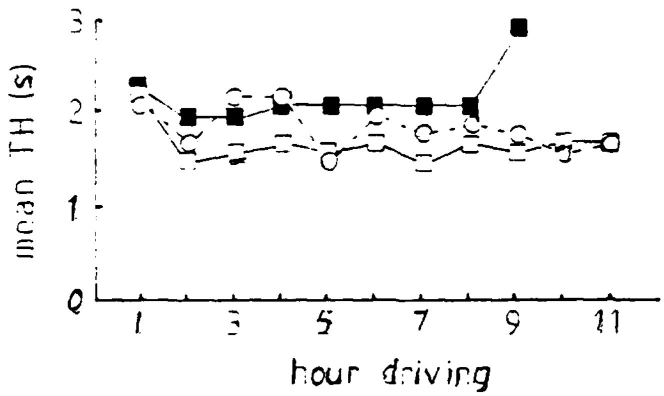


Figure 2 CLOSING TIME HEADWAY.

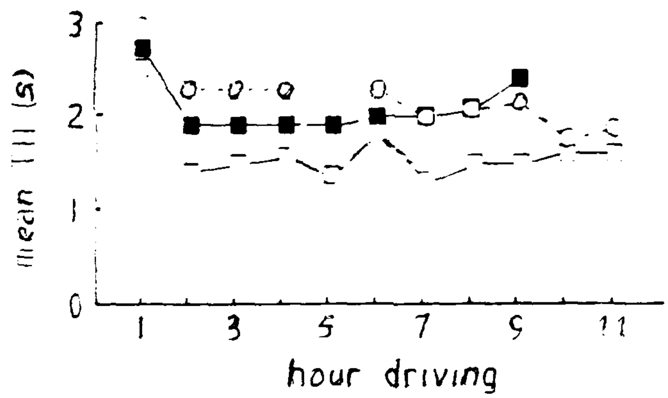
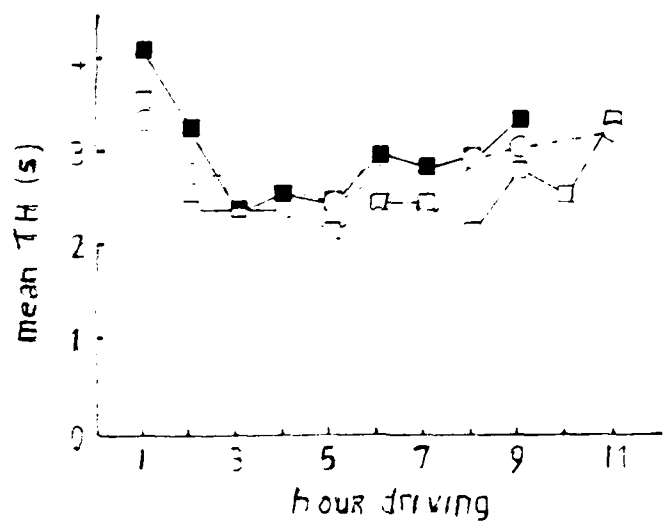


Figure 3. BRAKING CLOSING TIME HEADWAY.



Key o - o Normal following, n = 4 ■ Convoy 1. ■ - ■ Convoy 2. (all Figures)

Prolonged Heavy Vehicle Driving Performance:
Analysis of Different Types of Following Manoeuvre

Supplement 3

Summary

Three studies are reported which involve new analyses of the data of a series of studies, completed earlier, on the effects of a number of variables on the vehicle-following behaviour of truck drivers.

The first analysis examined evidence for differences in time headway between urban and rural open-road driving; the second involved a determination of the relationship between a driver's speed and his time headway; the third determined whether or not there were changes over time in the relationship between speed and time headway. Consideration of these analyses prompted a final examination of the driver's following distance at different speeds.

The results provided some evidence for a shorter time headway when driving faster on the open road and the correlation between speed and time headway was convincingly negative over all subjects and hours. Some suggestion of a decreased following distance at high speeds towards the end of a late shift (terminating at 02.30 hrs) was also found.

As to why drivers should adopt shorter time headways at higher speeds, two distinct, but not mutually exclusive, explanations were put forward. On the one hand, drivers seem to prefer a following distance of around 70 feet, with little concession to changes in speed. It is perhaps of great significance that it is at this distance that the angular velocity of a lead vehicle, which drivers use as a cue in maintaining headway, appears to have its greatest effect. On the other hand in adopting a particular speed and steady-state time headway, drivers may be responding to an estimate of the probability of hazards arising which would require rapid deceleration. Thus high speeds and short headways would both occur when such a probability was low (and vice-versa) and speed and time headway would become negatively correlated in the driver's following performance.

Time headway (TH) represents the time interval between two vehicles in a convoy or "following" situation. It is generally assumed (e.g. Lehman and Fox 1967) that below a TH value of about 1.5s, the shorter the driver's TH the more risky is the driving situation. This is to a certain extent self-evident and following too closely is regarded as a prevalent form of driver error (Helliar-Symons 1983). Other things being equal, a shorter TH is more dangerous than a longer TH.

If a short TH occurs during periods of high speed however, its accident potential is raised not just because the driver has less time available to react to sudden decreases in speed of the leading vehicle, but also because at high speeds control of his own vehicle may be reduced. Decreased control at high speeds may be exemplified by less responsive steering, a higher probability of skidding and by the greater distances required to bring the vehicle to a halt. In the light of the prevalence of rear-end collisions in road traffic accidents (see for example Colbourn, Brown and Copeman 1978) it is perhaps surprising that the relationship between a driver's speed and his or her concurrent TH appears to have been rarely investigated. However one study of direct relevance to this issue is that reported by Sumner and Baguley (1978). They found that close following by truck drivers on motorways occurred more frequently as speeds increased.

From research on the TH adopted by truck drivers under a variety of conditions (Fuller 1983, 1984) two strands of evidence lead to the proposition that TH may be inversely related to speed, with shorter TH at higher speeds and longer TH at lower speeds:

(1) In three studies of prolonged truck driving a longer TH was associated with periods of slowing down (closing-braking manoeuvre).

(2) In one study of drivers' following performance under normal driving conditions, and a second study in which drivers drove continuously in a two-vehicle convoy, periods of very short TH appeared to be associated with fast driving on rural, open roads. Conversely a longer TH appeared to be associated with much slower driving in an urban environment.

On the basis of these observations, a negative correlation between TH and driver speed may be predicted.

One way of conceptualising such a relationship between speed and TH is to think of the driver simply keeping a constant distance from the vehicle in front, irrespective of his speed. Thus as the vehicles slow down, entering a built-up urban area for example, an increase in TH will occur. Similarly as the vehicles speed up on the open road a progressive decrease in TH will occur. This relationship may be readily seen with brief perusal of the expression that relates distance and speed to time (distance/speed = time). If, as in the hypothetical example above, distance remains constant but speed increases, time (or TH) will decrease. In this way a shorter TH may become associated with higher speeds.

One further aspect of the relationship between speed and TH may be worth exploring and that is the possibility of its variation over time. It has been suggested that drivers may attempt to counteract a falling arousal level by following other vehicles more closely at higher speeds. If this suggestion is valid one would expect that for any given speed, but particularly at higher speeds, following distance should be shorter towards the end of a long trip compared with earlier.

These possibilities are examined below in a series of

reanalyses of the data of three studies reported earlier by the author (Fuller 1983). The first analysis attempts to clear the ground by presenting direct evidence for differences in TH in urban and open-road driving (point 2 above), using some observations made in a study of the effects of task uncertainty on truck driving performance, hereafter referred to as Experiment 3 (see Fuller 1983, Supplement 8 for details). The second analysis determines the overall correlation between speed and TH in the results for two other studies. One of these involved investigation of TH in the following performance of truck drivers under virtually normal driving conditions on a late shift starting at 15.00 hrs, hereafter referred to as Experiment 1 (see Fuller 1983, Supplement 6 for details). The other study involved a similar investigation with the major differences (a) that drivers drove the second vehicle of a two-vehicle convoy and (b) a day shift was included with onset time of 09.00 hrs. This study will be referred to hereafter as Experiment 2. A detailed report of it may be found in Fuller (1981). The third analysis looks at the possibility of changes over time in the relationship between speed and TH in the results for Experimemts 1 and 2. Where the strength of this relationship warranted it, a further analysis was undertaken of the association between speed and following distance, with particular emphasis on the relatively high truck speed, under our experimental conditions, of 40 m.p.h.

1: Comparison of TH in urban and open-road driving.

The aim of this analysis was to evaluate the impression described in (2) above, namely that periods of short TH tend to occur in open-road (usually rural) conditions and that periods

of long TH tend to occur in built-up, urban conditions.

Method

During part of the latter stages of Experiment 3, a novel procedure was introduced in which the observer in the rear van section of the experimental truck systematically allocated periods of driving to urban or open-road conditions as appropriate. Since this procedure was incorporated by the author only when he was taking a turn as observer at that time, it was restricted to one day's driving for subject 10 (Day 2 of the Uninformed condition) and two days' driving for subject 12 (Days 3 and 4 of the Informed condition). For each hour of driving the mean for the first 20 steady-state TH samples under each condition (urban v. open-road) was determined and the means were then compared using the Randomisation Test for matched pairs (Siegel 1956, pp 88-92). In this analysis, hours for which sample size < 8 were excluded as being unreliable, the two-day data for subject 12 were combined and the two subjects were treated as separate "experiments".

Results and discussion

For subject 10, shorter TH was reliably associated with open-road driving ($p = 0.008$) but no difference was found for subject 12 ($p > 0.05$). The relevant means for each subject are reproduced in Table 1 and presented graphically in Figure 1.

Although these results are based on a small sample of 23 hours of driving, there is clear confirmation of the expected urban v. open-road difference in one driver (S10). The observation that the same difference did not occur in the second driver (S12) points to the importance of individual differences in driving "style". The first subject (S10) may be described as someone who maintains a very safe TH in urban driving (mean = 2.7s) but who

significantly reduces TH when following in open-road conditions (mean = 1.3s). Since speeds were generally faster on the open-road (see Table 2), this driver cannot have increased his following distance to take full account of the higher speeds on the open-road. In fact his average distance headway actually decreased from 58 feet in urban driving to 41 feet in open-road driving.

On the other hand the second subject (S12) shows the same TH under both conditions (mean = 2.1s). And under both conditions that TH is objectively a safe one. Unlike S10, S12 does not significantly reduce TH when on the open-road. Thus he may rather be characterised as a "time-headway follower", that is one who maintains a relatively stable TH, adjusting distance headway as speed changes. His average urban distance headway was 55 feet and this increased to 64 feet in faster open-road driving.

Regardless of the validity of this distinction between two apparent styles of following behaviour, the important point to note from this analysis is that some evidence has been found which unambiguously reinforces the supposition that faster, open-road driving may occur with shorter time headway. As such this evidence lends limited support to the hypothesis of an inverse correlation between speed and TH.

2. Overall relationship between speed and TH in Experiments 1 and 2

The aim of this analysis was to determine the overall relationship between speed and TH in the results for Experiments 1 and 2. In the former study drivers drove under virtually normal driving conditions; in the latter in a continuous two-vehicle convoy configuration.

Method

The data for Experiments 1 and 2 were sampled to provide simultaneous speed and TH values. The data for drivers were analysed separately as were those for each hour of driving.

In Experiment 1 the sampling rate was at approximately 20s intervals over all steady-state TH episodes for each hour on all days. In Experiment 2 the sampling rate was at approximately 18s intervals beginning in the second quarter of each hour of Day 3. Because of the relatively enormous amount of data in this study, sample size for each hour was limited to $n = 40$. Where the data for a particular hour were missing (due originally to equipment failure) they were replaced with data for the same hour from days 2, 4 and 1 in that order until a sample size of $n = 40$ was obtained.

For each subject and for each hour of driving the Product Moment correlation coefficient was then determined. Using appropriate conversions to z scores (Chambers 1964) the overall mean correlations for each subject, condition and experiment were next obtained.

Results

The results for this analysis are presented in Table 3 for Experiment 1 and in Table 4 for Experiment 2. A graph showing the regression of TH on speed for the overall results of each experiment is presented in Figure 2.

It may be seen that without exception, all correlations between speed and TH were negative and significant where $p < .005$, thus providing strong confirmation of the expectation outlined in the introduction.

Analysis of correlation coefficients for subjects revealed

individual differences in the strength of the negative correlation. Thus in Experiment 1, subjects 3 and 4 had reliably weaker coefficients than subjects 2, 5 and 6 and subject 1 had a weaker coefficient than subject 2. In Experiment 2, subjects 2, 5, 6 and 11 generally obtained reliably weaker coefficients than the remaining subjects.

Comparing groups of subjects, in Experiment 1 no difference was found but in Experiment 2 the correlation was significantly weaker for early shift drivers and for younger drivers on the late shift.

Thus, in sum, higher speeds are generally associated with shorter time-headways and vice-versa; there are individual differences in the strength of this association; and in convoy driving it is weaker on the early shift and for the younger driver on the late shift.

3. Temporal aspects of the relationship between TH and speed in Experiments 1 and 2

Using the method outlined in Part 2 above, the Product Moment correlation coefficients for speed and TH were determined for each hour of driving in Experiments 1 and 2.

Results

Correlation coefficients for each hour for both Experiments 1 and 2 are presented in Table 5 and changes over time are represented graphically in Figure 3.

In the results for both experiments all coefficients were again negative and all were significant ($p < .005$). Comparing hours within Experiment 1, it was found that the coefficients for hours 5, 6 and 7 were weaker than for hours 4 and 11. In addition

those for hours 5 and 7 were weaker than for hour 10. Examination of Figure 3 reveals this pattern more clearly.

Within Experiment 2, the significance test revealed a rather complex pattern of differences between hours which is summarised in Table 6. In essence hours 7, 11, 3 and 10 had relatively weak correlations (in that order) whereas hours 1, 4, 9, 6, 5 and 2 had relatively strong correlations (see Figure 3).

Comparing equivalent hours for each experiment, there were no reliable differences in size of correlation coefficient for seven of the hour comparisons. However for hours 3, 10 and 11 the correlation was stronger in Experiment 1 than in Experiment 2 but vice-versa for hour 1. Again Figure 3 should help clarify these differences. It may be noted that although in Experiment 1 drivers showed some increase in the strength of the association between speed and TH from hour 7 onwards, this trend was not replicated in the combined results for Experiment 2 where drivers showed a decrease over hours 9 to 11.

Because of the general increase in strength of association between speed and TH over the last five hours of Experiment 1, a further analysis was undertaken on the data for those hours to determine drivers' average distance headway at the relatively high truck speed of 40 m.p.h. (legal maximum in Ireland). The question of interest was whether or not drivers tended to follow more closely at that speed as the trip wore on. Figure 4 presents a graph of the results of this analysis and reveals some evidence of a decrease over time in mean following distance at 40 m.p.h. Also plotted in the graph is mean speed for each hour which is seen to increase over time. The drop in following distance represents a TH decrease from 1.18s (hours 8 and 9) to 1.06s (hours 10 and 11).

It may be recalled that in the comparison of group effects in Experiment 2, a significantly stronger association between speed and TH was found for the late shift. On this shift a correlation coefficient very similar to the late shift of Experiment 1 was obtained (r (Exp. 2 late shift) = -0.50 and r (Exp. 1 late shift) = -0.48). The evidence reported in the previous paragraph suggesting a decrease in following distance at 40 m.p.h. over the last hours of driving in Experiment 1 prompted a search for similar evidence in the late shift results of Experiment 2. The results of this search are presented in Figure 5 where a decrease in following distance at 40 m.p.h. may be seen in the last two hours of driving. This represents a TH decrease from 1.60s for hours 8 and 9 to 1.26s for hours 10 and 11.

General discussion

These results confirm emphatically that there is a negative correlation between speed and TH: as a driver's speed increases his TH actually decreases. This relationship is pervasive across subjects and hours of driving, although it is stronger in some subjects than in others and stronger under certain conditions than others. Thus for example in convoy driving the negative correlation was stronger on the late shift, particularly for older drivers, and in normal driving was especially strong towards the end of the late shift. Analysis of this trend in terms of changes in distance headway at 40 m.p.h. (a relatively high speed for the experimental truck) produced some evidence for a decrease in headway at that speed over the last few hours of driving.

A negative correlation between speed and TH could arise in a number of ways. For instance it could arise with distance increasing with speed, but not increasing enough to maintain TH at its initial value. Alternatively it could also arise with distance actually decreasing as speed increased. It may be remembered that such a phenomenon was observed earlier in Part 1 where S10 was found to have not just a shorter TH but a shorter following distance when driving faster on the open road.

To throw more light on this issue an estimate of the relationship between a driver's speed and his following distance (i.e. distance headway) was determined from the hourly data for each subject in Experiments 1 and 2. The results for each subject are presented in Table 7. The overall correlation between speed and distance headway in Experiment 1 was $r = 0.37$ ($df = 51$, $p < .01$, two-tailed test) and in Experiment 2 was $r = 0.45$ ($df = 99$, $p < .01$, two-tailed test). However inspection of Table 7 shows

that there was marked variation amongst subjects, with the correlation coefficient ranging from -0.22 to +0.80. For 12 of the 18 subjects the relationship was not statistically reliable (two-tailed test). For the remaining 6 subjects the coefficient was significant and positive, indicating an increase in following distance with speed.

Since the correlation between speed and TH was invariably negative for all drivers, what these results imply is that although drivers generally increased their following distance as speed increased, they did not increase it enough to maintain TH at its initial level. Figure 6 illustrates this finding using the pooled data for each experiment separately. The figure shows the average distance headway of drivers at speeds of 20 m.p.h. and 40 m.p.h. and compares them with what they would have been if drivers had maintained the recommended TH of 1.5s at each speed. Although drivers follow further behind at the higher speed, they don't follow far enough behind to maintain a constant TH.

Because of the variation amongst individuals this generalisation should of course be taken with some caution. For three of the subjects studied here, a negative correlation between speed and distance was found (albeit not statistically significant), indicating a tendency to decrease distance despite increased speed. Such individual differences may ultimately be useful in discriminating accident prone drivers (see for example Evans and Wasielewski 1982). However it is far too early yet to draw such a conclusion.

Why should drivers, in adjusting their headways, undercompensate for speed increases, thereby opting for a shorter TH at higher speeds? According to Michaels (1965) and Janssen, Michon and Harvey (1976), in steady-state following drivers use

posited above as competing with that presented earlier in terms of the driver's preference for a 70 foot headway. Both factors of hazard expectation and 70 foot preference may have an effect in determining a driver's steady-state following distance, perhaps with the second factor prevailing where subjective estimates of hazards arising are very low. However it may be easier for drivers in a following situation to make distance judgements rather than TH judgements (which require an integration of speed and distance) and drivers may also prefer to stick to one kind of judgemental process rather than oscillate between two.

Temporal effects. Some suggestive evidence was found in both Experiments 1 and 2 for a decrease in following distance (at the relatively high speed of 40 m.p.h.) over the last few hours of driving on the late shift (see Figures 4 and 5). In Experiment 1 this represented an average TH decrease of 0.12s (to a TH of 1.06s) and in Experiment 2 an average TH decrease of 0.34s (to a TH of 1.26s). Thus in both experiments the reduction in TH was to a point below the recommended minimum headway and for Experiment 1 was to a point below the estimated average TH for that speed (1.40s).

What is of interest here is whether or not these observed changes have implications for safety in following. The answer to that question rests to some extent on what factor or factors were responsible for the observed headway decreases: under some conditions the driver may conceivably have left himself less time than he realised to respond to sudden decelerations of the lead vehicle. For example he may have adapted to a high speed and therefore been adjusting his headway on the basis of an underestimate of his real speed. On the other hand he may have been responding to a very low probability of some hazard requiring

of 0.9s; that is 0.6s (or 40%) below the recommended minimum headway of 1.5s. Even at 50 m.p.h. his TH would have to be as low as 1.1s.

However, counteracting this unsafe element in the safety equation is the tendency for steady-state following speeds to be highest where the probability of sudden velocity decreases in the lead vehicle is lowest: high speeds are associated with rural, open-road conditions with low traffic density and the absence of junctions, pedestrians and other hazards; low speeds are associated with just the opposite conditions. Thus when TH is shortest, the <u>need</u> for evasive action by a following vehicle, because of deceleration of the lead vehicle, should be the least. Of course, dangerous driving situations can arise where the low probability event of a sudden deceleration of the lead vehicle actually occurs. One may presume that multiple rear-end collisions on fog-bound motorways are instances of such a phenomenon.

An alternative explanation that would account for a negative correlation between speed and TH would be in terms of drivers' subjective estimates of the probability of some potential aversive event or hazard, arising in the traffic environment, which would require a major reduction in speed. Where such a probability was high, drivers would both drive more slowly and adopt longer headways; conversely where such a probability was low, drivers would drive at a higher speed and adopt shorter headways. In this way a driver's TH would become negatively correlated with speed, not because of some <u>causal</u> relationship between the two, but rather because both speed and TH were independently related to a third factor: the driver's estimate of the likelihood of a hazard arising.

It is not of course necessary to regard the explanation

the rate of change of the visual angle subtended by the lead vehicle (angular velocity) as the predominant cue in maintaining headway. However evidence reported by Perchonok and Seguin (1964) suggests that sensitivity to this cue is limited: its maximum influence is in headways of around 70 feet; it has little influence in headways over 100 feet and it has decreasing influence under about 50 feet (see review by McDonald 1984).

In order to maintain TH at a "safe" level (e.g. U.S. recommendation of 1.5s) as speed increases a driver must increase his following distance. However with increasing speed there comes a point where the appropriate safe following distance exceeds 100 feet. That point is a speed of about 46 m.p.h. The evidence from Experiments 1 and 2 shows that at this speed drivers opt for a headway much shorter than 100 feet: about 74 feet on average. In fact at no speed do they approach an average distance headway of 100 feet. This gives rise to the suggestion therefore that at these higher speeds drivers shorten their TH in order to continue using the angular velocity of the lead vehicle in the control of their following performance.

Figure 7 attempts to make this point more clear by plotting the relationship between speed and following distance for time headways of 2.5s, 1.5s and 1.0s. It may be seen that by shifting progressively from a longer to a shorter TH as speed increases, the driver can extend the range of speeds over which following may be maintained within the 100 foot angular velocity sensitivity range (to confirm this, simply project a vertical line down from points X, Y and Z in Figure 7). Also plotted in Figure 7 are estimates of the average distance headways maintained by drivers at different speeds in Experiments 1 and 2 (curve A-B). It may be noted that between speeds of 18 m.p.h. and 48 m.p.h. drivers

stayed on average within 10 feet of the following distance at which the angular velocity of the lead vehicle has its maximal effect (70 feet).

From this it appears that the negative correlation between a driver's speed and TH may be explained along the following lines. Drivers take some account of increasing speed by increasing following distance. However such increases in following distance are restrained by a preference for a headway of around 70 feet, a headway at which, at least according to the results of Perchonok and Seguin (1964), the angular velocity of the lead vehicle has its strongest influence. The net effect of this "restraint" (on increases in following distance with speed) is a decrease in TH.

A similar analysis to the above may be applied to situations in which steady-state following speed is relatively slow. By adhering to a region of 70 feet following distance, a driver's TH will gradually and inevitably increase with progressive decreases in speed (to see this, simply project a vertical line down from points P, Q and R in Figure 7).

Thus, in a nutshell, rather than maintain a "safe" headway by increasing distance as speed increases, drivers prefer a headway around 70 feet, the distance at which sensitivity to the angular velocity of the lead vehicle appears greatest. Some slight concession is made to increased speed - most subjects do follow at a greater distance - but at relatively high speeds this concession is inadequate to preserve a recommended safe TH.

This characteristic of drivers' following behaviour at different speeds clearly has implications for driving safety, particularly when extended to high speed driving. To remain within 10 feet of the preferred 70 foot distance when following another vehicle at 60 m.p.h., a driver would have to adopt a TH

braking by the lead vehicle (traffic density was lowest over the period in question). Alternatively he may have been following more closely in order to drive up a flagging arousal level (he would normally have been asleep for most of the period in question). Or again, at least in Experiment 1, he may have been trying to maintain a 70 foot headway despite a raised average speed (see Figure 4).

Although the evidence is not available to choose amongst these various explanations, other evidence, particularly relating to the driver's ongoing capability, is relevant to determining the riskiness of close following at high speeds. As summarised by Fuller (1983), on the late shift of Experiment 1, drivers became progressively more drowsy and older drivers rated themselves as more exhausted in the latter half of the shift. Similarly the end of the late shift in Experiment 2 was characterised by increases in drowsiness and exhaustion, coupled in this instance with a slight deterioration in rated performance; more daydreaming in younger drivers; a greater frequency of hallucinations and a general decrease in motivation. Although these changes were slight, taken together they do suggest the onset of a period of impaired capability. That in turn would imply that the driver would be less able to deal satisfactorily with a sudden emergency, should one arise.

<u>Conclusion</u>. It should be stressed that the bulk of this discussion has been concerned with generalities: with trends in the data which offer in particular the tantalising possibility that drivers tend to "lock on" to a 70 foot headway. But even if such

an interpretation is correct, at best it would account for perhaps 25%-30% of the variability in steady-state time headway. Hence other factors, such as the driver's estimate of the likelihood of sudden deceleration by the lead vehicle, should also be considered.

Furthermore this consideration of general trends tends to obscure the facts that there are important individual differences amongst drivers in their following behaviour and that the momentary determination of a driver's steady-state time headway is a complex issue. It is a justifiable exercise to attempt to construct the whole from the available fragments: but there are still many fragments yet to be discovered.

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Table 1. Mean steady-state time headway (in secs) for each hour under urban and open-road driving conditions

	Hour	Urban	Open-road
Subject 10	1	1.9	1.2
	3	2.0	1.0
	4	3.1	1.2
	5	2.4	1.3
	7	2.4	1.1
	8	4.3	1.7
	9	3.1	1.7
Subject 12	1	1.9	2.3
	2	2.5	2.4
	3	2.3	2.1
	5	2.5	2.0
	6	1.6	1.7
	8	2.1	2.0

Table 2. Mean speeds (and s.d.) for urban and open-road driving in m.p.h.

	Urban	Open-road
Subject 10	21.2 (5.3)	31.2 (3.2)
Subject 12	25.7 (5.6)	30.6 (3.1)

Table 3. Correlation coefficients* for speed and TH, Experiment 1

		r(subject)	r(age group)	r(overall)
Young	S1	-0.44		
	5	-0.55	-0.52	
	6	-0.56		
				-0.48 (n=1619)
Old	2	-0.59		
	3	-0.34	-0.44	
	4	-0.38		

*All coefficients are significant where $p < .005$

Table 4. Correlation coefficients* for speed and TH, Experiment 2

		r(subject)	r(age-shift group)	r(shift)	r(overall)
Early shift:					
Young	S2	-0.20			
	3	-0.40	-0.35		
	4	-0.45			
				-0.35	
Old	1	-0.47			
	5	-0.24	-0.34		
	6	-0.30			
					-0.43 (n=4887)
Late shift:					
Young	9	-0.55			
	10	-0.48	-0.43		
	11	-0.23			
				-0.50	
Old	7	-0.58			
	8	-0.57	-0.57		
	12	-0.55			

	r(age)
Young	-0.39
Old	-0.46

*All coefficients were significant where $p < .005$

Table 5. Correlation coefficients* (between speed and TH for each hour: Experiments 1 and 2

Hour	Experiment 1	Experiment 2
1	-0.44	-0.62
2	-0.50	-0.46
3	-0.53	-0.32
4	-0.65	-0.54
5	-0.38	-0.46
6	-0.43	-0.47
7	-0.31	-0.25
8	-0.50	-0.41
9	-0.48	-0.47
10	-0.56	-0.35
11	-0.62	-0.25

*All coefficients are significant where p < .005

Table 6. Results of significance test for differences between hours: Experiment 2

r for hours	7, 11 < 8, 2, 5, 6, 9, 4, 1
	3 < - 2, 5, 6, 9, 4, 1
	10 < ——— 6, 9, 4, 1
	8 < ————— 4, 1
	2, 5, 6, 9 < ——————— 1

Table 7. Correlation coefficients between speed and distance for each subject in Experiments 1 and 2. The slope and intercept for the regression of distance on speed are also included. Values are derived from mean speed and following distance for each hour (n = 11).

		r	slope	intercept
Experiment 1	S1	0.43	0.61	25.1
	2	0.52	0.72	25.6
	3	0.51	0.88	26.4
	4	0.28	0.31	37.2
	5	0.58*	0.50	32.4
	6	-0.23	-0.30	57.2
Experiment 2	S1	0.40	0.63	23.8
	2	0.46	1.01	21.5
	3	0.75*	0.97	26.6
	4	-0.22	-0.28	68.7
	5	0.62*	0.36	37.4
	6	0.69*	0.73	25.6
	7	0.12	0.16	56.3
	8	0.07	0.20	57.9
	9	0.76*	1.00	30.2
	10	-0.22	-0.64	82.8
	11	0.80*	0.92	26.9
	12	0.47	0.67	27.1

*p < .05 two-tailed

FIGURE 1. Steady-state TH in urban and open-road conditions: Subjects 10 and 12

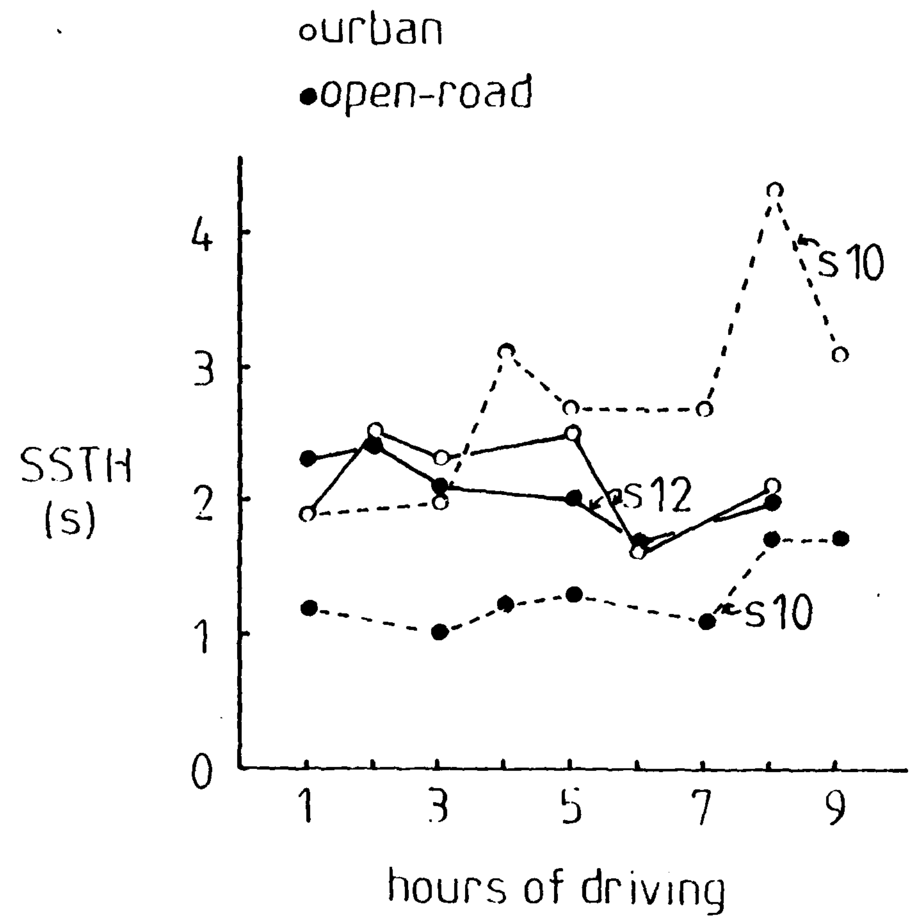


FIGURE 2. Regression lines of TH on Speed for all subjects, Experiments 1 and 2

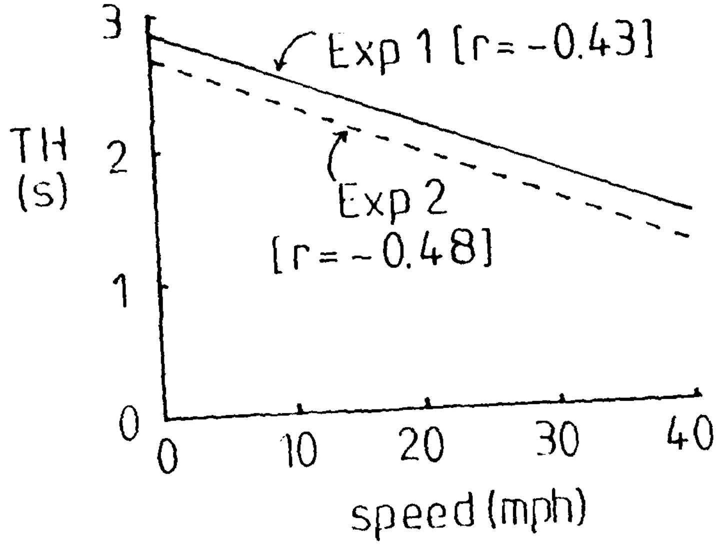


FIGURE 3. Mean Product Moment r between speed and TH for each hour of driving, Experiments 1 and 2

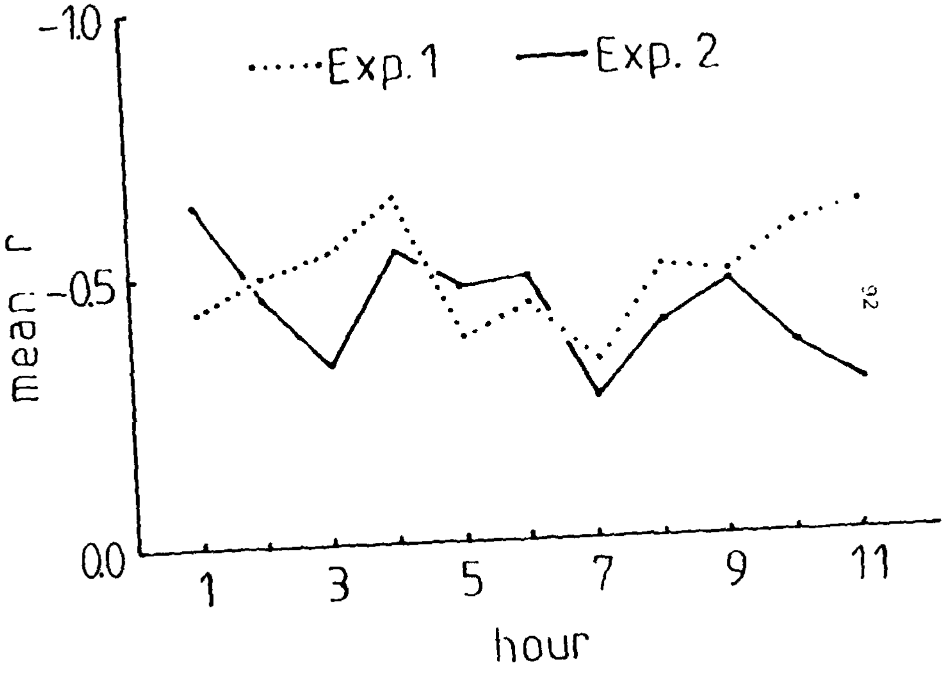


FIGURE 4. Mean distance headway at 40 mph and mean speed for hours 7-11. Experiment 1

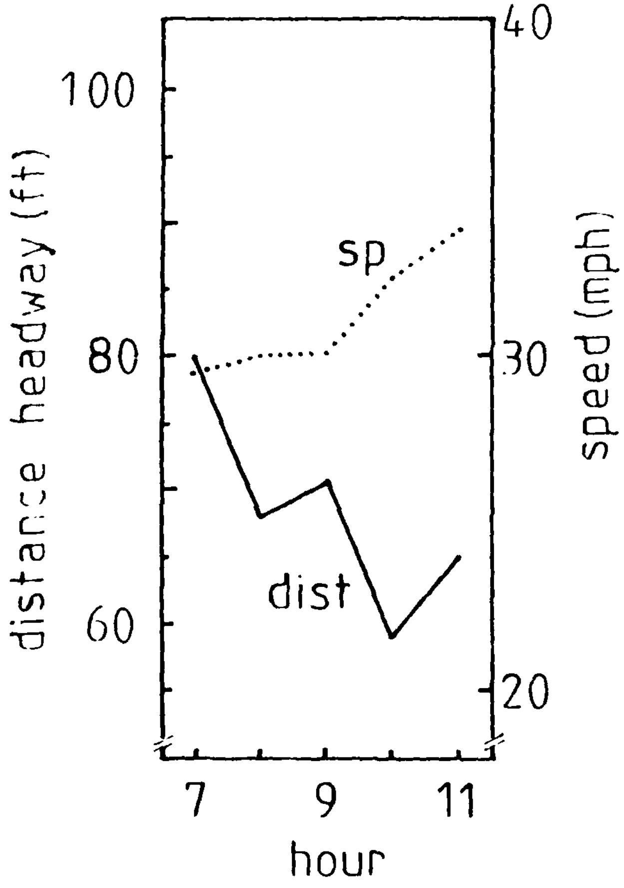
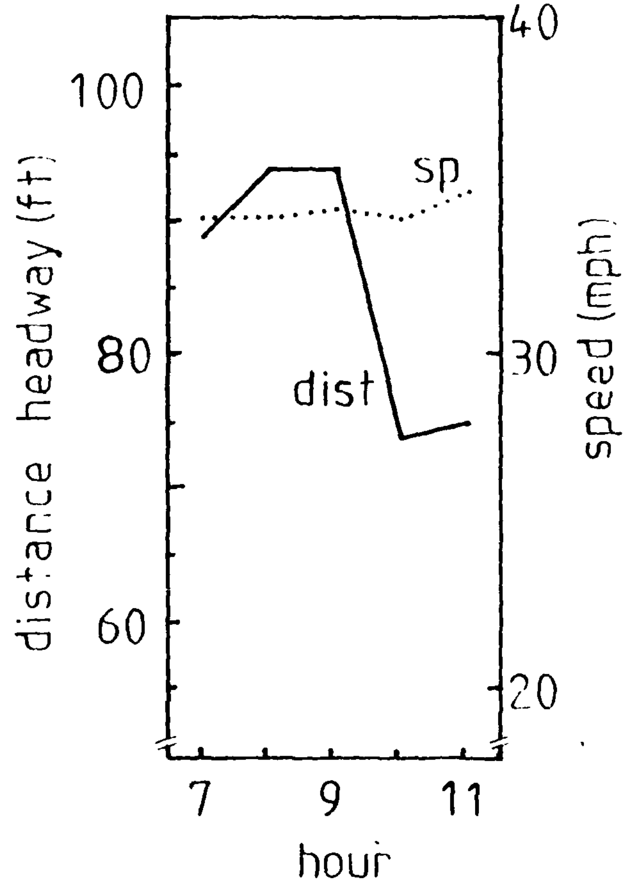


FIGURE 5. Mean distance headway at 40 mph and mean speed for hours 7-11. Experiment 2, late shift



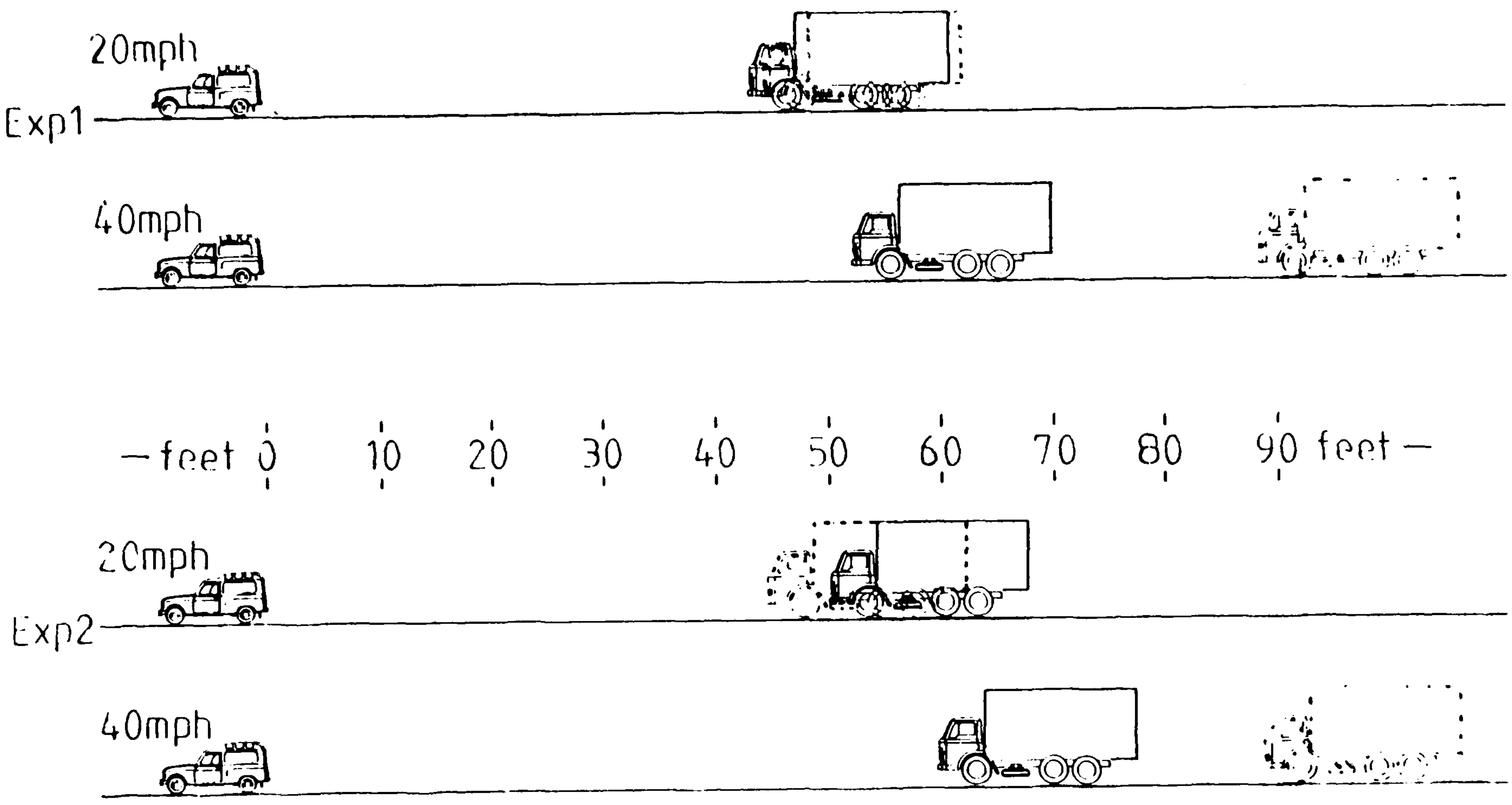


FIGURE 6. Mean distance headway of drivers at speeds of 20 mph and 40 mph in Experiments 1 and 2. 'Ghost' truck shows distance where TH is 1.5s. Vehicle separation distances are to scale (2mm:1ft)

FIGURE 7. Speed and following distance for time headways of 2.5s, 1.5s and 1.0s in relation to the range of influence of lead vehicle angular velocity (horizontal lines) and the estimated following performance of drivers in Experiments 1 and 2 (curve A-B)